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Devoted to Science and the Mechanic Arts

Vol. 220 SEPTEMBER, 1935 No. 3

PHYSICS APPLIED TO TUBERCULOSIS.*

BY

POL. N. CORYLLOS, M.D.

Our organism is a laboratory in which continuous physiochemical reactions take place, mostly oxidation. Fats, carbohydrates and proteins are burned supplying the necessary energy for continuation of life and growth. During these processes oxygen is consumed and CO_2 and H_2O are produced. Therefore these reactions cannot be carried on unless O_2 is supplied and CO_2 eliminated by a well regulated mechanism.

Respiration and circulation represent the most important factors of that rather complicated mechanism in which internal secretions, vitamins and even inorganic catalysers play an important part. Respiration insures the supply of O_2 and elimination of CO_2 in the lung and in the tissues. Circulation regulates through the circulating blood the distribution of O_2 to the tissues, according to their action and continuously varying metabolic needs, and, on the other hand, it renders possible the elimination of CO_2.

In fact, respiration and circulation can be considered as one function, the only objective of which is, as Claude Bernard put it, " to preserve constant the conditions of life in the internal environment, the blood."

* Presented at a meeting held Thursday, March 28th, 1935.

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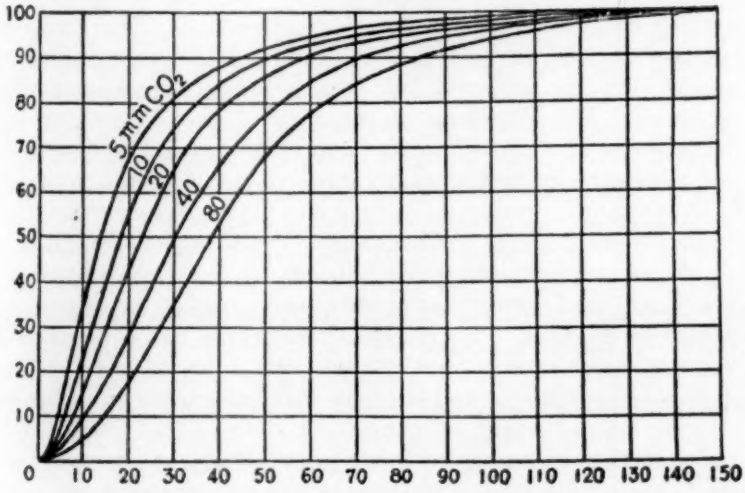
On the other hand, Paul Bert has shown that the physiological action of gases dissolved in the blood depends on the pressures which they exert in the surrounding atmosphere, that is to say on their vapor pressures; therefore, says Haldane, we may conclude that it is the diffusion pressures of substances dissolved in the blood that corresponds to Claude Bernard's "conditions of life."

The regulating mechanism of these two functions, respiration and circulation, is a marvel of precision, accuracy and efficiency. The rate and depth of respiratory movements, and the velocity and volume of the circulating blood in the different organs are regulated by special bulbar centers; however the final regulation of these centers is under the dependence of the partial tension of O_2 and CO_2 in the tissues. Even the slightest excess of CO_2 in the tissues, so slight that it cannot be determined by our most sensitive electrometric methods brings about an increase of the depth of respiratory movements and of elimination of CO_2 through the lungs; in that way the ratio of CO_2 to alkali of the blood, and consequently hydrogen ion concentration remains absolutely constant. Changes in the pH of the blood, says Haldane, even as small as the difference between the pH of distilled and ordinary water, if not rapidly corrected are not compatible with life. Conversely when the vapor tension of CO_2 drops, (a condition called acapnia by Henderson) alkalosis is produced, and respiratory movements are slowed or even suspended, allowing the accumulation of CO_2 in the blood and the reëstablishment of the normal tensions of CO_2.

The regulation of partial tensions of O_2 in the blood and the tissues is not so strict as of CO_2. They can present relatively marked variations without any immediate untoward effects. This is fortunate; in fact it should not be forgotten that whereas there are reserves in our organisms of fats, carbohydrates, proteins, hormones and other substances necessary for continuation of life from which our organisms can draw in case of emergency, there is no storage of oxygen other than the small amount contained in the lungs. This is about 600 cc., that is the amount sufficient for the metabolic needs of a man of average weight and at rest for two minutes only. Oxygen deficiency when moderate can be easily tolerated, even when it is prolonged. In high altitudes for

example it is compensated by the increase of the number of red cells and the total amount of hemoglobin. But when oxygen tension drops below 50 mm. Hg, symptoms of severe anoxemia appear. It is of importance to remember here, that the clinical symptoms and the severity of anoxemic disturbances depend to a great extent upon the concommittant tensions of CO_2. Thus when anoxemia is due to obstruction of the respiratory ways or to the excessive limitation of the respiratory field, during which CO_2 cannot be eliminated, the clinical picture is of asphyxia with cyanosis, respiratory anxiety and gasping for air. On the contrary when during shallow or rapid breathing caused by anoxemia in acute or chronic disease of the lung, enough pulmonary parenchyma remains to allow the elimination of the very diffusible CO_2, the clinical picture is altogether different. Lowering of the tension of CO_2 produces alkalosis and slowing of respiration, periodic breathing or even apnea. Therefore there is no respiratory anxiety or gasping for air. Moreover, when the CO_2 pressure is low, hemoglobin takes up larger amounts of oxygen, so that the percentage of oxyhemoglobin increases although the amount of oxygen has remained unchanged (Fig.

FIG. 1.



Curves representing the percentage saturation of hemoglobin with oxygen at different partial pressures of oxygen and CO_2. Dog's blood at 38° C. Ordinates = percentage saturation with oxygen; abscissæ = partial pressures of oxygen in millimeters of mercury. (Bohr, Hasselbach, and Krogh.)

1); but physiologically the deficiency of O_2 has increased, because, as Bohr has shown, this oxyhemoglobin holds on to its oxygen more strongly than when pressures of CO_2 are normal and there is not enough free oxygen to satisfy the needs of the tissues. These patients die without any of the clinical symptoms of asphyxia such as cyanosis, gasping for air and anxiety. They do not struggle for air; death comes rapidly and unheeded both by the patient and the physican when the latter is not familiar with this " Bohr effect." A number of deaths in pulmonary tuberculosis following hemoptysis or surgical operations and more especially in lobar pneumonia are due to combined deficiency of O_2 and CO_2, although they are generally ascribed to such vague causes as heart failures, cardiac dilatation or respiratory failure. Only administration of O_2 combined with CO_2 can correct this condition.

ORGANIC CHANGES OF THE LUNG.

Thus in the last analysis respiration and circulation are regulated by the partial tensions of O_2 and CO_2, their indexes of diffusion and solubility, and their affinity to combine with hemoglobin and alkali. However, accurate and automatic adaptation of these functions to the everchanging conditions of tissue activities will be possible only as long as the organs in which they are accomplished remain normal. It is evident that any organic alteration of the lung parenchyma, acute or chronic will be followed by corresponding functional disturbances. Modifications of pressure in the pleural cavity affecting the movements of the lung, changes in the diameter of the bronchi impairing pulmonary ventilation and renewal of alveolar air, alteration of the permeability of the respiratory membrane hampering gas exchanges, cause serious functional disturbances which often, in pulmonary diseases, exceed in importance and severity the disorders caused by the morphological changes. Therefore, there seems to be no excuse for the neglect of the physics and mechanics of the lung so far shown by medical and surgical men interested in pulmonary diseases. In fact, it cannot be denied that recent advances in the treatment of lobar pneumonia are entirely due to a better study of the physics of the pneumonic lung. As it will be shown here, the marked progress in the understand-

ing of pulmonary tuberculosis and its treatment, which has been accomplished very recently, are greatly, if not entirely, due to new conceptions of the disease originated from a better study of the physics and mechanics of the tuberculous lung.

For a better comprehension of these advances it will be helpful to review a few points of the anatomy, mechanics and physics of the normal lung.

ANATOMY.

The lungs are contained in the thoracic cavity. They represent two perfectly elastic organs composed of myriads of small respiratory balloons, the alveoli, which are connected by small tubes, the bronchi with a common tube, the trachea. During inspiration air penetrates through the trachea into the bronchi and the alveoli, and it is expelled from them during expiration.

The chest cavity represents a cage, the bars of which are the ribs which give to it its characteristic rigidity. The thoracic muscles enclose it anteriorly, posteriorly and laterally. Its inferior opening is closed by the diaphragm which separates the chest cavity from the abdominal cavity.

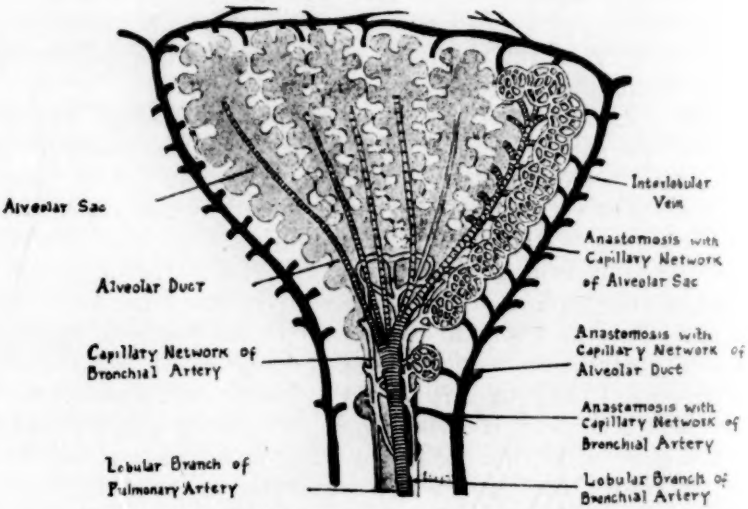
The lungs are thus contained in an air-tight, closed cavity. The external surface of the lung and internal surface of the chest are lined by a serosa which is called the pleura. Between the two layers of the pleura there is normally a *virtual* cavity which is the pleural cavity.

The ribs, during inspiration, are pulled upward by the contraction of the respiratory muscles and cause increase of the anteroposterior and transversal diameters of the chest cavity. The vertical diameter is increased by the contraction and lowering of the diaphragm. During expiration, on the contrary, the drop of the ribs and the rise of the diaphragm produce the opposite effect. These rhythmic changes of the capacity of the thoracic cavity force the lungs to expand during inspiration and collapse during expiration. It is obvious that the lungs are forced to follow the movements of the chest because of the absence of air between the two layers of the parietal pleura. As soon as air is introduced into the pleural cavity, the lungs, which are dilated in the chest cavity, will collapse obeying their elasticity. Under normal condi-

tions, the elastic pull exerted upon the parietal layer of the pleura, that is, the layer which covers the internal surface of the chest wall will be greater during inspiration than during expiration. Therefore, the pressure in the pleural cavity will be subatmospheric and measures the elastic recoil of the lung. Under normal conditions it varies between − 5 and − 9 mm. of Hg. The chest cavity is divided by a vertical partition called the mediastinum in two completely separate cavities. One is the right and one the left, each of which is occupied by the corresponding lung. The trachea, the heart and the large vessels are placed between these two lungs in the mediastinum and can be moved with it.

The walls of the respiratory alveoli, which represent the anatomical unit of the lung, are extremely thin. They measure less than 6/1000 mm. In the external surface of them we find a rich net of capillaries in which circulates the venous blood which is brought to the lung from the right heart by the pulmonary arteries. Thus this blood is separated from the air present in the alveoli by an extremely thin membrane which is semi-permeable. It is through this "respiratory membrane" that the gases of the air diffuse

FIG. 2.


Alveolar Sac
Alveolar Duct
Capillary Network of Bronchial Artery
Lobular Branch of Pulmonary Artery
Interlobular Vein
Anastomosis with Capillary Network of Alveolar Sac
Anastomosis with Capillary Network of Alveolar Duct
Anastomosis with Capillary Network of Bronchial Artery
Lobular Branch of Bronchial Artery

Scheme of the blood vessel distribution in the lung (after Sauerbruch).

into the blood and, conversely, the gases in solution in the blood pass into the alveolar air (Fig. 2). This all-important gas exchange is accomplished according to the physical laws of partial gas tensions, diffusion and solubility indices.

MECHANICS

The lungs, being smaller than the chest cavity, are obliged to stretch in order to fill this cavity. Normally they do so, because the pressure in them is equal to the outside atmospheric pressure, while around them, that is; in the pleural cavity, the pressure is negative as was said before. Therefore, when a hole is made in the chest wall or in the surface of the lung and air is allowed to enter in the pleural cavity, the intrapleural pressure becomes less negative and, consequently, the lung collapses. Under these conditions the lungs do not follow the movements of the chest and renewal of the air contained in the alveoli cannot take place. But as the blood continues to circulate around the alveoli, it is obvious that the composition of the alveolar air tends to become similar to the composition of the air dissolved in the blood. Therefore, at some time the partial tensions of O_2 and CO_2 present on either side of the respiratory membrane should become equal and, no diffusion of these gases take place. In fact, however, such an equilibrium is never reached because of the very marked differences of the speed of diffusion of the three gases present in the air, that is; of CO_2, O_2 and N_2. These differences are especially due to the greater solubility of CO_2 than of O_2 and O_2 than N_2 and, due to the fact, that the alveolar endothelium and the walls of the capillaries represent wet semi-permeable membranes. This important point will be discussed later.

The atmospheric air is composed in round figures of 80 per cent. N_2 and 20 per cent. O_2. The respective partial tensions of these gases at sea level, the pressure of the mixture being 760 mm. of Hg, are 608 mm. of Hg. for N_2 and 152 mm. for O_2. In the atmospheric air, we find only 0.03 per cent. of CO_2 corresponding to a partial tension of 2.2 mm. Hg. In the venous blood the percentages of O_2 and CO_2 are respectively 5 and 6 per cent. corresponding to partial pressures of 38 and 45 mm.

The percentages and the partial pressures of the same gases in the alveolar air are different. We find in it 15 per cent. of oxygen, 5 per cent. of CO_2 and again 80 per cent. of N_2. The corresponding partial tensions of these gases are 115 mm. Hg for O_2, 38 mm. for CO_2 and 608 mm. for N_2 (Fig. 3). In reality the partial tensions are smaller because the

FIG. 3.

Percentages and Partial Pressures of Oxygen, Carbon Dioxide and Nitrogen in Alveolar Air and Venous Capillary Blood.

Gas.	Alveolar Air.		Venous Blood.	
	Per Cent.	Partial Pressure in Mm. Hg.	Per Cent.	Partial Pressure in Mm. Hg.
Oxygen	15	114	5	38.0
Carbon dioxide	5	38	6	45.6
Nitrogen	80	608	..	608.0

alveolar air is saturated with water and the partial pressure of vapor is 49 mm. of Hg which must be subtracted from the pressure of the mixture.

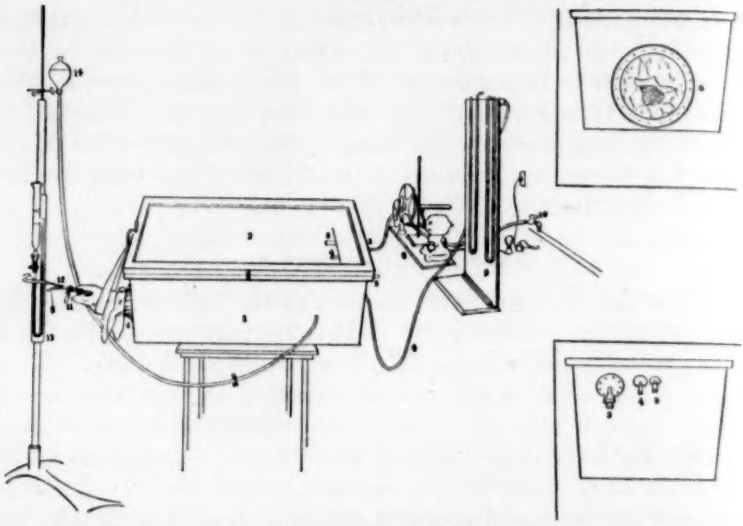
But even if we do not take into consideration the partial tension of vapor, we find a tremendous discrepancy between the partial tensions of O_2 and CO_2 in the atmospheric air and in the alveolar air, although the latter communicates freely with the outside air. This curious phenomenon is explained by the extraordinary activity and the speed of gas exchanges through the respiratory membrane. It suffices to be reminded that, although, the circulating blood remains in the lung for one second only, complete saturation of hemoglobin is accomplished in the first fifth of that second. This speed of gas exchanges is even more marked in small animals, such as, the goldfish, where the blood remains in the lung only for 1/10 of a second. Here, again, the hemoglobin is saturated with oxygen in the first fifth of that time. This speed of gas exchanges leaves a considerable margin of safety in cases of pulmonary diseases in which inflammatory edema of the respiratory membrane decreases considerably its permeability to gases.

These differences are further explained by the fact that the air is only partially renewed in the lung. The total capacity of the lungs is about 4,000 cc., whereas, the volume of the tidal air, that is; the amount of air going in and out of the lungs in each respiration is, at rest, only 500 cc. This is 1/8 of the air contained in the lungs. On the other hand, as Keith has shown we use only 1/10 to 1/20 of our lung, under ordinary conditions.

BRONCHIAL OBSTRUCTION.

When the air contained in a part of the lung is completely cut off from the outside air, it is obvious that the composition of the alveolar air will present more marked changes. This occurs when a bronchus is obstructed. As was mentioned above theoretically an equilibrium should be established between the partial pressures of the alveolar and venous gases and from that time on no changes should occur. In fact, what occurs is that the gases contained in the alveoli are absorbed by the blood circulating in the peri-alveolar capillaries in a relatively short time. The mechanism of this peculiar phenomenon was studied experimentally by Dr. Birnbaum and myself in the laboratory of surgical research of Cornell Medical College. These experiments consisted of obstructing a bronchus in a dog which had been anesthetized with sodium amytal solution. This was injected into the peritoneal cavity. The obstruction of the bronchi was produced by especially constructed catheters which were introduced into the lung by means of the bronchoscope. These catheters were so constructed that a specimen of air could be taken for gas analysis from the alveoli situated in back of the obstructed bronchus (Fig. 4). By taking a specimen every two minutes, it was possible to represent graphically the course of the changes of the partial pressures of O_2 and CO_2. In this curve, it is shown that the percentage of O_2 in the entrapped air drops very rapidly from 15 to 6 per cent., while the percentage of CO_2 rises from 0.03 per cent. to 5 or 6 per cent. Then the percentage of O_2 drops while the percentage of CO_2 rises and again the percentage of O_2 rises while CO_2 drops. This process goes on until the alveolar air is absorbed completely (Fig. 5).

FIG. 4.



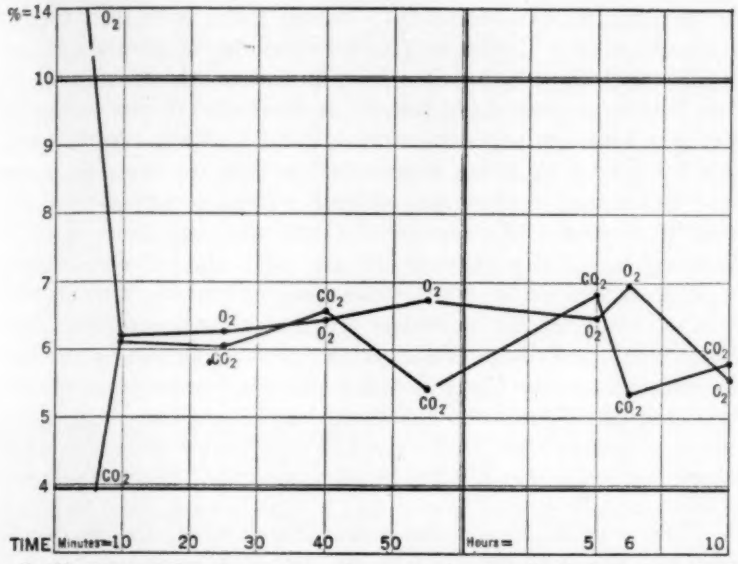
Lay-out of the open chest experiment in the oscillating vacuum box. After the chest is opened the animal is placed in the air-tight box (1) the cover of which (2) is made of plate glass. The head of the animal protrudes through the opening in the box, and the rubber tissue cuff attached around this opening (6, and upper left corner enclosure 6) is fixed around the neck of the animal, previously shaved and anointed with petrolatum, by a bandage (7). The rotating valve (8), interspersed between the suction apparatus (10) and the box inlet (3) insures an oscillating vacuum in the box. This pressure is measured by the water manometer (9) and is equal to the negative intrapleural pressure of the animal taken previous to operation. Inlet (5) serves to regulate the pressure in the box. A rubber tube passes through one wall of the box and is connected to a reservoir with physiologic solution of sodium chloride; by this means fluids can be administered under the skin or into the peritoneum of the animal during the experiment. Through the bronchoscope (11) the bronchial cannula is introduced into the left stem bronchus, and the balloon which is to occlude the bronchus is then inflated by means of the syringe-mercury manometer arrangement described in Fig. 6. The large tube of the cannula, in communication with the entrapped intrapulmonary air, is closed off unless samples of air are to be withdrawn through it for gas analysis. (Coryllos & Birnbaum.)

From the study of these curves, we were able to understand the intimate mechanism of the absorption of O_2, CO_2 and N_2 and formulate a new theory explaining these phenomena. This is presented in the following figure (Fig. 6).

Levy and Schroetter have conducted similar experiments on the human with results identical with ours. The objective of their work was to obtain an accurate determination of the partial tensions and percentages of O_2 and CO_2 in the alveolar blood.

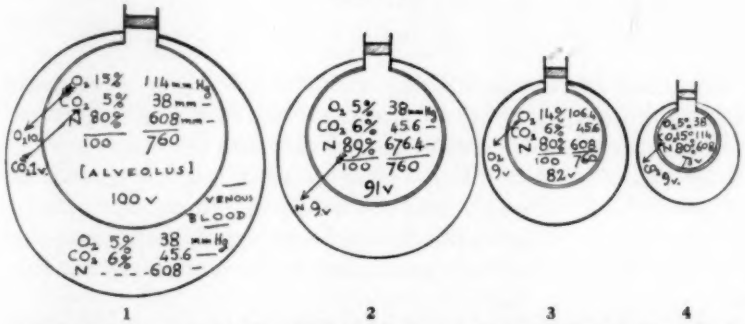
When the air is absorbed, the lung shrinks and becomes airless and is called atelectatic. An atelectatic lung is identical with the fœtal lung before the first inspiration. Thus, when a bronchus is obstructed and, only when it is completely

FIG. 5.



Graphic representation of percentages of oxygen and carbon dioxid obtained by alveolar gas analysis before obstruction and for a period of over 10 hours after obstruction of the right lung. Dog 482.

FIG. 6.



A schematic representation of alveolar gas exchanges, gradual gas absorption and shrinkage of the alveoli after complete bronchial obstruction. The absolute volume of the alveolus is only approximately indicated, but the figures given are relative and demonstrate perfectly well the principles involved. In 1, ten volumes of oxygen diffuse into the venous blood and one volume of carbon dioxide diffuses out of the venous blood into the alveolus. In 2, the alveolus has now lost nine volumes of gas as stated under (1) and the oxygen and carbon dioxide have come into equilibrium in the venous capillary blood and in the alveolus. However, the percentage and partial pressure of nitrogen have now been increased so that nine volumes of nitrogen diffuse out of the alveolus into the venous blood. In 3, nine volumes of nitrogen having previously diffused out of the alveolus into the venous blood, the percentage and partial pressure of oxygen or carbon dioxide have been relatively increased. For purposes of explanation let us say the oxygen has been thus relatively increased in percentage and partial pressure. Nine volumes of oxygen are now ready to diffuse out of the alveoli into the venous blood. In 4, nine volumes of oxygen having diffused from the alveolus into the blood, we can now consider that the carbon dioxide in the alveolus is relatively increased by these nine volumes. Thus the partial pressure of this gas is relatively increased and carbon dioxide is ready to diffuse out of the alveolus. Thus the cycle continues until all the gases of the lung are absorbed, although actually the gas exchanges are going on simultaneously and not in the isolated way which we have ideally considered. (Coryllos and Birnbaum.)

obstructed, atelectasis is produced in the part of the lung corresponding to that bronchus. When there is only a partial obstruction of a bronchus it is not atelectatic shrinkage but, on the contrary, emphysematous dilatation which may occur. This " obstructive emphysema " is produced in the following manner: During inspiration the bronchi dilate and air can pass by the obstructing object or the mucosa forming a one way valve and enter the alveoli. During expiration the bronchi retract and are closed completely by the agent of obstruction. Thus ingress of air into the alveoli during inspiration is possible while expiratory egress becomes impossible. Thus air accumulates in the alveoli causing their emphysematous distention. Atelectasis and obstructive emphysema should be born in mind when we come to study the evolution of tuberculous cavities.

TUBERCULOUS LUNG.

Three capital morphological changes occur in the parenchyma of the lung infected by the tubercle bacillus.

1. Inflammatory infiltration and edema.
2. Caseous necrosis of the affected lung parenchyma.
3. Development of fibrous tissue in the involved areas.

Inflammatory edema and thickening of the pulmonary parenchyma and of the alveolar membrane hamper gas exchanges and cause deficiency of the supply of oxygen and of the elimination of CO_2. Thus anoxemia and cyanosis are produced, the intensity and duration of which, are proportionate to the extent and the duration of the inflammatory changes of the lung. But also anoxemia with acapnia may develop.

Caseous necrosis of a portion of the parenchyma leads to the formation of tuberculous cavities following the elimination of the caseated material through a bronchus. These cavities, which are holes in the lung containing air, represent the most important characteristic feature of pulmonary tuberculosis. As it will be shown their formation is connected with and regulated by the physics and mechanics of the lung. It is because of these cavities that Laennec said that tuberculosis

may develop in any organ but phthisis develops only in the lung.

The development of fibrous tissue is of great importance in the disease. It causes definite changes in the permeability of the respiratory membranes and leads to permanent bronchial obstructions and physiological exclusion of large segments of the lungs. But also it represents the principal factor of cure of the disease; the mechanism of this cure so far considered as mysterious and unexplainable is easily understood as will be shown by the changes occurring in the physics and aërodynamics of the tuberculous cavities.

The above enumerated pathological changes are not limited to the respiratory membranes of the lung. They also affect, and even to a greater extent and at an earlier date, the small and medium sized bronchi of the involved areas of the lung. Whatever may be the nature of these changes, inflammatory edema, caseous necrosis or fibrosis, they all lead to stenosis and obstruction of the bronchi, and consequently to atelectasis. Atelectasis is of paramount importance in pulmonary tuberculosis. In fact the tubercule bacillus is a strictly aërobic microörganism; oxygen is absolutely necessary for its growth and continuation of life. Novy and Soule and more recently Loebell, Richardson and Shorr have shown that when cultures of human tubercle bacillus are deprived of oxygen for as short a time as 10 days, their respiratory metabolism falls to zero, they cease growing and only 30 per cent. of the organisms remain alive when placed again in favorable conditions. This fact gave us the key to the solution of a vital problem in tuberculosis, namely that microbes may remain alive for years when encapsulated in a fibrous shell without growing and without giving rise to any clinical phenomena. And then, following an acute infection which breaks this fibrous shell, these tubercle bacilli start to grow and become active. The explanation is simple; as long as oxygen was both mechanically and biologically screened by their fibrous shell they could not grow; but when oxygen was allowed to reach them again a number of them were revived and did manifest their activity by clinical signs and symptoms.

TUBERCULOUS CAVITIES.

The importance of the application of physics to pulmonary tuberculosis becomes more evident when we come to the study of the tuberculous cavities. The importance is not only theoretical; it is of great practical interest. In fact the whole question of treatment of pulmonary tuberculosis gravitates today around the closure of these cavities by mechanical means. Closure of cavities brings about disappearance of tubercle bacilli from the sputum, improvement of the general condition and clinical cure of the disease. Thus active surgical treatment tends to replace today the routine hit-and-miss treatment by bed rest, and hopeful expectation. The two outstanding surgical procedures actually used are artificial pneumothorax and thoracoplasty. Both aim at the mechanical collapse of the diseased lung. Therefore it has become urgently necessary to learn more about the physics of these cavities and the mechanics of their production and of their closure. I shall enumerate here a few of the fundamental and so far insoluble problems related to these cavities. Tuberculous cavities appear spherical in the radiographic films of the living patient while they are irregular and ragged in the lung examined at the autopsy table. Why?

These cavities sometimes close spontaneously; more frequently they increase in size, generally slowly and progressively; but also, occasionally they present rapid increase in size so that within a few weeks they may double in size as if they were inflated, and then again decrease in size. Why? As a rule following artificial pneumothorax they gradually retract and finally disappear. However not uncommonly we also see cavities increase under pneumothorax; and, although air is present all around the cavity, a simple thin adhesion of the cavity to the chest wall is sufficient to prevent closure; the section of this adhesion, by the procedure known as closed pneumolysis causes closure of the cavity in over 50 per cent. of these cases. Why?

Likewise, thoracoplasty produces closure of cavities and clinical cure of the disease in 60 to 80 per cent. of all cases of pulmonary tuberculosis in which the cavity is situated in the upper part of the lung. Occasionally however the cavity remains open. Why?

To the questions enumerated above none of the theories so far proposed have given a satisfactory answer. Such answers as " Nature has the tendency to produce cure of tuberculosis by the development of fibrous tissue " cannot be accepted. In fact neither has anybody proven so far this partiality of Nature in favor of our cells and against the microbes, nor do these conceptions explain the failure of this same Nature to produce spontaneous cure in 80 per cent. of tuberculous cavities. Another theory was advanced, according to which there are around the cavities two sets of fibers; one of concentric fibers which tends to produce retraction and closure, and one of radiating fibers which tends to produce the opposite effect. Unfortunately for this theory such fibers have never been seen under the microscope, nor is it possible to understand the action of the radiating fibers when the lung is collapsed and is not anchored to the chest wall by adhesions. Other authors offered explanations based on changes in the elasticity of the lung. For Parodi, Van Allen and others the elasticity of the diseased lung is increased, for Demarest and Lefevre, it is decreased, for Bendove the elasticity of retraction is increased whereas the elasticity of expansion is decreased. It is impossible to understand these changes in elasticity of the lung. As the elasticity of the lung is a function of the elastic fibers of this organ, and since destruction of elastic tissues takes place in all diseases of the lung in general and in tuberculosis more particularly it is difficult to believe that the elastic tension of this organ can be increased under any circumstance. As for the distinction of elasticity in one of retraction and one of expansion, each of them acting independently from the other, we must confess that we cannot see it.

On the contrary when weeding out these unwarranted, unsupported and metaphysical theories, we turn to the study of physics and mechanics of these cavities, the whole question is flooded with new light and the explanation of the capricious and puzzling behavior of tuberculous cavities becomes clear and simple.

In fact a cavity is nothing else than a hole in the lung communicating through a small bronchial outlet with the bronchial tree of the lung and through it with the outside atmosphere. Thus the pressure inside the cavity is equal to one atmosphere,

whereas that around the cavity is equal to the subatmospheric intrapleural pressure. Thus the pressure within the cavity being higher than that outside of it, its shape is necessarily spherical, for obvious mechanical reasons. On the contrary, after death, when the lung is extracted from the chest, the differences in pressure inside and outside the cavity no longer exist, and the shape of the cavity becomes irregular. This answers the question of the shape of these cavities.

Let us consider now a cavity with its bronchial outlet which is called also the draining bronchus, and focus our attention upon the latter.

1. It may remain open and the cavity will communicate freely with the outside world. Conditions for the development of tubercle bacilli are favorable because of the presence of large amounts of oxygen. The knowledge of this detail gives a real meaning to the expression frequently used of " open tuberculosis " by which we designate the active cases in which great numbers of bacilli are present in the sputum. This conception is corroborated by the analysis of the gaseous content of the cavity, which shows that O_2 and CO_2 are almost in the same proportions as in the atmospheric air, and by the measurement of the variation of pressures in the cavity which are the same as those in the bronchi.

2. The bronchial outlet of the cavity may become obstructed. Inflammatory edema, caseous infiltration or fibrotic retraction of the mucosa and the wall of the bronchi lead to the same effect. Hence the metaphysical conception that " nature tends to cure of the disease." From what was said above it is easy to foresee the changes which will occur in the cavity. The first effect is that the microbes present in the cavity are not able to pass into the bronchi; thus the sputum of the patient becomes negative for tubercule bacilli although the cavity is still visible in the radiographic films. Second, the air, and especially the O_2 contained in the cavity will be absorbed. The cavity will thus shrink, as any part of the lung does under similar conditions. On the other hand disappearance of oxygen will cause the arrest of the development of tubercle bacilli and of their toxins. Thus the heretofore puzzling phenomena of the disappearance of tubercule bacilli from the sputum, of the gradual closure of the cavity and of

the cessation of toxic manifestations and improvement of the patient find a simple and clear explanation. Of course the speed of closure of the cavities will be controlled to some extent by the thickness of their walls, the mechanical resistance that these walls offer and the degree of diffusion of gases possible through them. It is obvious also that closure of the bronchial outlets may occur spontaneously and that in these cases it may be temporary or definite, more frequently the first. On the contrary when the lung is surgically collapsed its bronchi become collapsed or kinked; thus the definite closure of the bronchial outlets of the cavities is greatly facilitated. This conception seems simple and convincing in contrast to the vague theory by which "collapse treatment produces cure of the disease by putting the lung at rest."

Experimental evidence further corroborates our theory; gas analysis of the air contained in those cavities shows that oxygen is very low and rapidly disappears, while the pressure within these cavities becomes negative and oscillations are absent.

3. A third variety of changes may occur in the bronchial outlet of the cavity. Its lumen may become only narrowed so that during its inspiratory dilation air can enter into the cavity while during its expiratory collapse it becomes obstructed and air is entrapped in the cavity. The mechanism is the same as in obstructive emphysema occurring in foreign bodies of the lung as described above. Under these conditions the cavity becomes inflated and increased in size; it is called "check valve cavity" by Ornstein. When this check valve mechanism ceases because of advancing necrotic lesion, the inflation of the cavity will cease. On the contrary, when complete obstruction of the bronchus is produced the cavity gradually disappears. This theory is supported by clinical and experimental evidence. An analysis of the gaseous contents of these cavities shows lower percentages of oxygen than in the alveolar air and higher percentages of CO_2 than in the atmospheric air. Most significant are the positive pressures found in these cavities.

The interest of the above developed conceptions is not only theoretical. It is also eminently practical. They have shown us that the key for the treatment of tuberculous

cavities is not to be looked for in their walls but in their bronchial outlets. I am satisfied that guided by this knowledge our efforts are no longer wasted; the rapid advances accomplished every day in our surgical methods for treatment of this disease, the splendid results so far obtained by them and the speed with which this field has been enlarged are positive proof of the importance of the application of physics in pulmonary tuberculosis.

A SHORT ACCOUNT OF THE THEORY OF LUBRICATION.[1]

IV. TEMPERATURE RISE AND TEMPERATURE DISTRIBUTION IN BEARINGS.

BY

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The modern understanding of lubrication is based on the equations of the hydrodynamic theory. These equations, as has been seen, describe the performance of a bearing in terms of the actual film viscosity but, of course, this depends on the temperature of the film, which in general is unknown. We have next to consider whether there is any way of calculating or predicting the steady running temperature of a bearing. It is not commonly realized that there is a rational solution for this problem. The solution depends both on the rate of generating heat by friction, and on the rate of heat transfer from the bearing to its surroundings.

HEAT GENERATED BY FRICTION.

It follows from the first law of thermodynamics, provided heat quantities are measured in work units, that the rate of generating heat is equal to the power expended in overcoming frictional resistance. It is therefore equal to the product of the frictional resistance, fW, by the rubbing speed, πDN, as shown by Eq. (21) of Section I; and may also be written

$$H = \pi NPD^3 \left(\frac{L}{D}\right) f, \qquad (1)$$

where P denotes W/LD, the load per unit area; D the journal diameter; L the length of the bearing at right angles to the direction of motion; and f the coefficient of friction.

[1] From public lectures given at Brown University, 1934, and repeated at Yale University, under the New Haven Section, A.S.M.E., 1935; last installment of a series beginning in the June issue of the JOURNAL, page 677.

For the lightly loaded full bearing at high speeds we have already seen from Petroff's law that

$$f = 2\pi^2 \left(\frac{D}{C}\right)\frac{ZN}{P}, \qquad (2)$$

where C denotes the clearance, or difference in diameters; and Z the viscosity of the film. In any of the more complicated applications such as partial bearings, or the full bearing at lower speeds, there will be some characteristic equation, or curve, corresponding to Eq. (2) and connecting the coefficient of friction with the generalized variable ZN/P and with the design factors such as C/D and L/D.

These *characteristic* equations are purely mechanical relations connecting the coefficient of friction with the instantaneous viscosity, quite apart from any consideration of the temperature of the bearing. It will be one of our objects to show how the characteristic equation for a bearing may be transformed into the corresponding *working* equation, from which the unknown viscosity has been eliminated.

As a numerical example of the heat generated by friction, reference may be made to the problem of the grinding machine discussed at the end of Section I. The data needed for Eqs. (1) and (2) may be summarized as follows: $N = 20$ rev. per sec., $P = 40$ lbs. per sq. in., $D = 3$ in., $L/D = 2$, $C/D = 1/1000$, and $Z = 30$ cp. $= 4.35 \times 10^{-6}$ lb. secs. per sq. in. at the assumed temperature of the film. From these data it was found that $H = 485$ ft. lbs. per sec. Dividing by the mechanical equivalent of heat, 778 ft. lbs. per B.t.u., we obtain $485/778 = 0.623$ B.t.u. per sec. for the rate of generating heat in this bearing. From the definition of the thermal unit, this would be sufficient to raise the temperature of 0.62 lb. of water one deg. F. per sec., or 37 lbs. of water one deg. per min.

TEMPERATURE RISE IN THE LUBRICANT.

In the above example, if all the heat generated were to remain in the film we might compute the rate of temperature rise, $d\theta/dt$, from the rate of generating heat per unit volume of lubricant upon dividing this rate by the heat capacity of the lubricant per unit volume, h. The last mentioned quantity is a useful property of liquids equal to the product of the specific heat by the density. For an oil of specific gravity 0.90 having a specific heat about 0.45 that of water [2] (Ref. 11), $h = 136$ inch pounds per cubic inch per degree.

[2] The specific heat of water is about 778 ft. lbs. per lb. per deg. F. and its density 62.3 lbs. per cu. ft., therefore the heat capacity of water per unit volume,

Taking for the clearance volume $\pi DLC/2$ = 0.0848 cu. in. and for the total rate of heat generation H = 485 ft. lbs. per sec. or 5,820 in. lbs. per sec., we have for the rate per unit volume of lubricant 5,820 divided by 0.0848 = 6,860 in. lbs. per sec. per cu. in. The maximum, or adiabatic, rate of temperature rise $d\theta/dt$ is therefore 6,860 divided by 136; approximately 500 deg. F. per sec. or 25 deg. for each revolution of the shaft. This would seem reasonable when converting nearly one hp. into heat and concentrating it within a film of oil having a volume less than 1/10 of a cu. in. Evidently such a rate could not long continue without some means of escape for the heat.

To carry away all this heat by oil circulation as fast as it is generated would require a flow rate Q equal to H/hT units of volume per unit time, if the temperature rise in the outgoing oil is limited to T deg. above the temperature of the incoming oil. Suppose the oil comes in at 70° F. and leaves at 130°, so that T = 60 deg. F. Then with H/h equal to 5,820 divided by 136, as before, Q must be equal to 0.71 cu. in. per sec., or about 11 gal. per hr.

In practice the situation would be intermediate between the two extremes. The heat generated is by no means confined within the clearance space, neither is it entirely carried away by the oil (Refs. 1, 2, 17). A large part of the heat is, of course, conducted through the shaft and the bearing to the exterior surfaces, where it escapes by radiation and convection.

The rate of heat transfer from the lubricating film to the more remote surroundings is greater the greater the temperature elevation, T, above the surroundings. On this account, alone, the temperature rise would necessarily take place at a diminishing rate, as time goes on, after starting up a machine from rest. Another factor which also contributes to a diminishing rate is the drop in viscosity with rising temperature, provided the bearing is operated under stable conditions, so that a drop in viscosity reduces the frictional resistance. The net effect is that in practice the temperature-time curve for the bearing rises at a progressively diminishing rate, levelling off flat when the permanent running temperature has been reached. This temperature may be defined as the temperature of thermal equilibrium; a temperature just high enough, relative to that of the surroundings, to maintain a rate of heat transfer equal to the rate of generating heat by frictional resistance.

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h, is about 48,500 ft. lbs. per cu. ft. (more simply, lbs. per sq. ft.) per deg. F.; or 337 lbs. per sq. in. per deg. F. The value for a mineral oil will be 0.45 times 0.90 as great, or 136 lbs. per sq. in. per deg. F. For the dimensions of thermal units see Table 2 of Section III.

HEAT TRANSFER AND TEMPERATURE ELEVATION.

The rate of heat transfer from a bearing to its surroundings at any instant is independent of the amount of power being dissipated into heat, and for a particular installation depends solely on the temperature elevation. For a given temperature elevation, T, the rate of heat transfer, H', is not only independent of the *amount* of the power loss, H, but it is wholly uninfluenced by the manner in which this power is converted into heat. It would be the same, for example, if the power were being dissipated by ohmic resistance in an electrical heating coil concealed in the clearance space, instead of by friction. In short, there is no physical connection between H' and H. The important relation is that connecting H' with T. This fact provides the clue to the problem of calculating the permanent running temperature of a bearing.

Newton's law of cooling, which is accurate enough for practical use at moderate temperature elevations (say T less than 50 degrees F.) states that

$$H' = C_0 T, \tag{3}$$

where C_0 is a constant for the particular installation. A less accurate but more customary form of Newton's law is

$$\alpha_1 = \frac{H'}{A} = C_1 T, \tag{4}$$

where A is the total area of the bearing housing, computed in some conventional way, and α_1 denotes the rate of heat transfer per unit area.

Conversion factors for some of the units in common use are given to three significant figures by Table 1. It is convenient to remember that one square meter is approximately 10.8 square feet, and that a temperature interval of one degree C. is equal to 9/5 or 1.8 degrees F. In abbreviated computations it is good practice to reserve the degree symbol (°) for actual temperatures on the scale, indicating temperature differences or intervals by the notation *deg.*

From experiments on various types of bearing housings it was found by Lasche (Ref. 1) that the rate of heat transfer per unit area of the bearing surface could be very well repre-

TABLE 1.

Power and Heat Flow Units.

(*a*) *Conversion from inch pounds per second:*

One in. lb./sec. =

8.33×10^{-2} foot pound per second (ft. lb./sec.)
1.52×10^{-4} horsepower (hp.)
1.13×10^{-4} kilowatt (kw.)
3.86×10^{-1} British thermal unit per hour (B.t.u./hr.)
9.73×10^{-2} Wärme Einheit [3] per hour (W.E./hr.)
2.69×10^{-2} calorie per second (cal./sec.)

(*b*) *Conversion into inch pounds per second:*

One ft. lb./sec.	=	12	in. lb./sec.
" hp.	=	6600	"
" kw.	=	8850	"
" B.t.u./hr.	=	2.59	"
" W.E./hr.	=	10.3	"
" cal./sec.	=	37.1	"

[3] Identical with the kllogram-calorie.

sented by the formula

$$\alpha_2 = \frac{H'}{\pi DL} = C_2 T^{1.3} \tag{5}$$

for temperature elevations from about 50 to 200 degrees F. The dimensions of the constant C_2 are given in Table 2 of Section III. This formula is now generally accepted, although the problem is one that offers a considerable field for further investigation. The influence of radiation, as distinguished from conduction and convection, is evident from the exponent of T. Accordingly we may anticipate numerical exponents greater than 1.3 when the temperature elevation is sufficiently increased.

A convenient constant for Newton's law in still air is found to be 2 British thermal units per hour per square foot per degree F. measured at the outer surface of the bearing housing. This is a round number based upon the literature of free convection; and is in close agreement with experiments by Karelitz (Ref. 14) on oil-ring bearings. It appears from these experiments, which were on 4-inch by 8-inch bearings, that the temperature drop measured from the outer surface averaged about half the total temperature elevation T. Hence for use with Eq. (4) in still air C_1 = approximately one

British thermal unit per hour per square foot per degree F. This is equivalent in round numbers to 4 Wärme Einheit per hour per square meter per degree C.

The constant of Eq. (5) as found by Lasche for full bearings, with large housings, in still air is $C_2 = 17$, when α_2 is expressed in Wärme Einheit per hour per square meter of bearing surface, and T in degrees C.; or 2.9 when α_2 is in British thermal units per hour per square foot, and T in degrees F. Lasche states that for infinitely thin shells the heat transfer rate would be about one-sixth of the foregoing, while for ordinary bearings cooled by the motion of adjacent machinery it might be three or four times as great.

As a numerical example consider the 3-in. by 6-in. bearing previously discussed, which was running at 100° F. Assuming 77° F. for the room temperature, the temperature elevation T would be 23 deg. From Lasche's formula, Eq. (5), $\alpha_2 = 2.9$ times $(23)^{1.3} = 171$ B.t.u. per hr. per sq. ft. of bearing surface. The bearing area is 18π divided by 144, or 0.39 sq. ft. The calculated heat transfer rate H' is therefore .39 times 171, or 67 B.t.u. per hr. in still air. From Newton's law of cooling, Eq. (4), with $C_1 = 1$, and taking arbitrarily 8 times the bearing surface for the effective area of the housing, $H' = 8$ times .39 times 23, or 72 B.t.u. per hr. Averaging the two results and allowing a factor of 2 for the influence of air currents, we may estimate, roughly, 140 B.t.u. per hr. for the heat transfer rate, H', so long as this bearing continues to run at a temperature elevation $T = 23$ deg. F.

CALCULATION OF THE PERMANENT RUNNING TEMPERATURE.

Since the rate of heat generation for the bearing in question was shown to be of the order of 0.62 British thermal unit per second or 2,240 per hour at 100° F., it is evident that this machine can run only *intermittently* at any such temperature. The *permanent* running temperature, with the given lubricant, must be considerably more than 23 degrees above the room temperature. The general procedure necessary for calculating the permanent running temperature of a bearing was outlined and applied by the author in 1915 (Ref. 3); and has been discussed more recently by Gümbel, Falz, Kiesskalt, and others (Refs. 25, 28, 37 of Section II; Refs. 4, 10, 16, 21, 26 below).

Under thermal equilibrium conditions the heat transfer rate is equal to the rate of generating heat in the bearing, therefore $H' = H$. These two quantities are numerically

equal when expressed in the same units, and may therefore be used interchangeably. This of course would not be universally true; thus during the long warming up period before thermal equilibrium has been reached H is greater than H'; and when the machine is suddenly stopped, $H = 0$, but H' remains finite, and diminishes only very slowly. At first sight the equilibrium problem is a confusing one.[4] Since $H' = H$ and we have definite relations like Newton's law connecting H' with T, the most obvious move would be to calculate T from H. This attempt is frustrated by the fact that H depends on the viscosity, Z, which is unknown and depends on T. However, it will be seen that the problem must be determinate, since there are three independent relations available from which to solve for the three unknowns H, Z, and T.

These three fundamental relations are (1) the heat transfer law for the particular bearing and cooling system; (2) the characteristic equation or curve for the friction loss of the bearing, in terms of the instantaneous viscosity; and (3) the viscosity-temperature curve for the lubricant. They may be symbolized by

$$H = f_1(T), \tag{6}$$

$$H = f_2(Z), \tag{7}$$

$$Z = f_3(T). \tag{8}$$

In these equations f_1, f_2, and f_3 are known functions; and for the time being, such quantities as the length, diameter, and clearance of the bearing, the load, speed, viscosity at room temperature, and all thermal properties that may be involved are treated as constants.

To illustrate the use of Eqs. (6) to (8), which in practice may be available either in analytical or graphical form, consider the previous numerical example. From Newton's law of cooling, Eq. (4), taking $A = 8\pi DL = 3.14$ square feet, and $C_1 = 2$ British thermal units per hour per square foot per degree F., we find $AC_1 = C_0 = H'/T = 6.3$ British thermal units per hour per degree F. Referring to Table 1, this is

[4] Further discussion will be found in Refs. 3 and 4 of Section I; 19 and 39 of Section II; 5, 6, 20, 23, and 25 below.

seen to be equivalent to 2.59 times 6.3, or 16.3 inch pounds per second per degree F. Hence with $H' = H$ we have for the concrete form of (6)

$$H = 16.3T, \tag{9}$$

provided H is expressed in inch pounds per second, and T in degrees F.

From Eqs. (5) and (7) above, or Eq. (22) of Section I, we find upon substituting the values $D/C = 1{,}000$, $L/D = 2$, $N = 20$ revolutions per second, and $D = 3$ inches, that

$$H = 1.34\ (10)^9 Z \tag{10}$$

provided H is expressed in inch pounds per second, and Z in pound seconds per square inch. Eq. (10), then, is the concrete equivalent of (7) for the problem in hand.

The lubricant will be assumed to have the characteristics of an ordinary paraffin base oil of 30 centipoises, or 4.35×10^{-6} pound seconds per square inch, viscosity at 100° F. From the data given for Oil A in Table 2 of Section I we find by interpolation from a smooth curve [5] that the relative viscosity at 100° referred to the standard temperature of 77° is 0.52. Dividing the long interval from 122° to 212° into two equal parts we find in the same way for the relative viscosity at 167°, 0.136. Passing a simple hyperbola through these two points, and converting from relative to absolute viscosity,[6] we have at any temperature θ, and for any temperature rise T above the room temperature of 77 degrees,

$$Z = \frac{1.03\ (10)^{-4}}{\theta - 76.4} = \frac{1.03\ (10)^{-4}}{T + 0.6}. \tag{11}$$

Eq. (11) serves as a convenient approximation for the viscosity, Z, in pound seconds per square inch when T and θ are expressed in Fahrenheit degrees; and provided applications

[5] Plotting the logarithm of the relative viscosity against the logarithm of the temperature in deg. F.

[6] Let the relative viscosity Z/Z_{77} be represented by $k/(\theta - c)$; then at 100° F., $0.52 = k/(100 - c)$ and at 167° F., $0.136 = k/(167 - c)$. From these two equations $k = 12.3$ and $c = 76.4$. We also have $Z_{77} = Z_{100}/.52$ and $Z_{100} = 4.35 \times 10^{-6}$. Therefore $Z_{77} = 8.37 \times 10^{-6}$ and $Z = 8.37(10)^{-6}$ times the expression $k/(\theta - c)$. Substituting the values of k and c leads immediately to Eq. (11).

are not required at temperatures too far removed from the two points arbitrarily selected for defining the curve.

Equations (9), (10), and (11) may be solved simultaneously giving roughly $T = 92$ deg. F., $Z = 1.12 \times 10^{-6}$ lb. sec. per sq. in. or 7.7 cp., and $H = 1{,}490$ in. lbs. per sec. Thus the film temperature will have climbed up to $77 + 92$, or 169° before the permanent running temperature is reached. There is no change in room temperature. The effective viscosity and the loss will then be reduced to approximately one-quarter of their values for intermittent operation at 100°. We should expect from the observations of Harelitz that the outside temperature of the housing might be of the order of $77 + 92/2$ or 123° F.—not too hot to touch. All these results, however, may be greatly influenced by the area, shape, and ventilation of the housing; the conductivity of the metal; and even by the color of the paint (as affecting radiation). While the effects of these several factors may be combined in a single empirical constant as in Eq. (9) above, their exact determination is a problem for future research.

When the temperature range and precision required are such as to justify a more elaborate computation we may apply Lasche's law in the form [7]

$$H' = 5.95T^{1.3} \tag{12}$$

together with Slotte's equation [8]

$$Z = \frac{0.69}{\theta^{2.6}} = \frac{0.69}{(T + 77)^{2.6}} \tag{13}$$

in place of Newton's law of cooling and the hyperbolic viscosity-temperature curve. From (10) and (12) since $H' = H$,

$$5.95T^{1.3} = 1.34\ (10)^9 Z. \tag{14}$$

Replacing Z in this equation by its equivalent from (13) and taking the 1.3 root of both sides we arrive at the cubic equation

$$T(T + 77)^2 = 2.03\ (10)^6. \tag{15}$$

Now write $T = T_1(1 + \delta)$ where T_1 is any arbitrary value of the order of magnitude of the expected temperature rise, and δ a small fraction. Substituting in (15), expanding, and retaining only the first and second powers of the unknown

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From Eq. (5) with the constants previously discussed, again introducing the factor of 2 for ventilation, and converting H' into in. lb./sec. by reference to Table 1.

[8] From Eqs. (13) and (14) of Section I, the constants being obtained from the best representative straight line for $\log Z/Z_{77}$ plotted against $\log \theta°$ F. The mean deviation of this line from the smooth curve for Oil *A* is less than one per cent. over the range from 77° to 212° F. or beyond.

quantity δ reduces (15) to a quadratic, whose solution is easily obtained. Starting with a trial value of $T_1 = 90$ deg. F. we find $\delta = -0.10$ and $T = 81$ deg. Repeating with $T_1 = 80$ gives $\delta = +0.02$, from which $T = 81.6$ deg.

The foregoing method of numerical solution may be applied with any heat transfer exponent β provided the constants of Slotte's equation can be so adjusted that the exponent b is a simple multiple of β; or vice versa. In the first solution above, $b = 1 = \beta$; in the second solution, $b = 2.6 = 2\beta$.

ANALYTICAL TREATMENT.

The influence of the design factors and thermal characteristics of the bearing and lubricant may best be shown by carrying through a purely symbolic solution. It will be assumed that the temperature rise is small enough to permit the use of Newton's law of cooling and the equilateral hyperbola for the viscosity-temperature curve, while at the same time ZN/P is large enough to satisfy Petroff's equation. Under these conditions the general equations (6), (7), and (8) may be written

$$H = C_0 T, \tag{16}$$

$$H = BZ \tag{17}$$

and

$$Z = \frac{a}{T + T_0}, \tag{18}$$

respectively, where

$$B = 2\pi^3 D^3 \left(\frac{L}{D}\right)\left(\frac{D}{C}\right) N^2 = B_0 N^2 \tag{19}$$

in accordance with Eqs. (1) and (2); and a is the viscosity-temperature constant from the formula $Z = a/(\theta - c)$. The constant T_0 is defined by $T_0 = \theta_0 - c$, and may therefore be interpreted as the elevation of the room temperature, θ_0, above the apparent solidifying temperature of the lubricant, c.

Equations (16) to (18) may be solved simultaneously for T, Z, and H in terms of T_0, a, B, and C_0. It follows from dimensional analysis that the relative temperature elevation T/T_0 must be some function of the single variable $aB/C_0T_0^2$. The detailed algebraic solution gives

$$\frac{T}{T_0} = \tfrac{1}{2}(-1 + \sqrt{1 + k_1 N^2}), \tag{20}$$

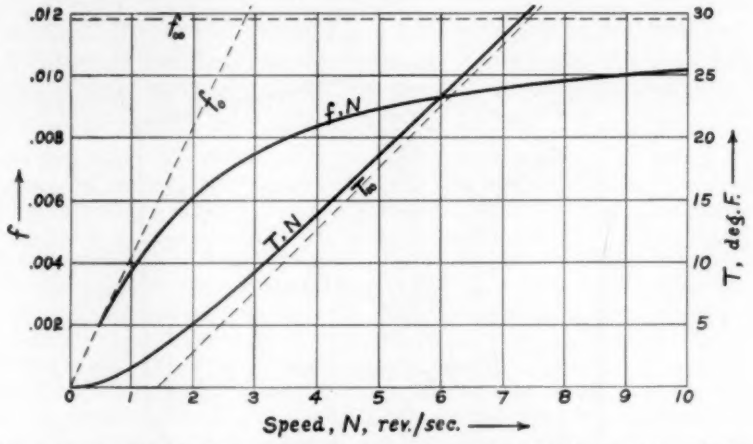
where $k_1 = 4aB_0/C_0T_0^2$. The original value $T = 92$ degrees will again be obtained upon substituting the appropriate data.

We are now in a position to construct the *working* equation for a high speed full journal bearing—a direct relation between the coefficient of friction, f, and the speed, N, without reference to the unknown viscosity of the film. Substituting from (20) into (18) and from (18) into (2)

$$f = \frac{k_2 N}{P}\left(\frac{2}{1 + \sqrt{1 + k_1 N^2}}\right), \qquad (21)$$

in which k_2 denotes $2\pi^2(D/C)a/T_0$, or $2\pi^2(D/C)Z_0$ where Z_0 is the viscosity at room temperature.

FIG. 1.



Temperature rise, T, and friction coefficient, f, of a full journal bearing under thermal equilibrium conditions, from Eqs. (20) and (21).

Eqs. (20) and (21) have been plotted in Fig. 1 for the values $k_1 = 0.495$ sec. squared, $k_2 = 0.166$ lb. sec. per sq. in., and $T_0 = 14$ deg. F. These values are based on the same bearing constants B_0 and C_0 but with revised constants for the lubricant, $a = 1.18(10)^{-4}$ and $c = 63$ deg., to obtain more precise results near the room temperature.[9] From (20) it will be seen that for small values of N the ratio T/T_0 is equal to $(k_1/4)N^2$ while for larger values it approaches $-(1/2) + (\sqrt{k_1}/2)N$.

It is interesting to note from (21) that at lower speeds the

[9] The revised constants are obtained by fitting the hyperbola at $\theta = 77°$ and 167° F., instead of 100° and 167° F.

coefficient of friction is given by k_2N/P, corresponding to Petroff's equation with Z_0 in place of Z; and that the coefficient approaches a maximum limit [10]

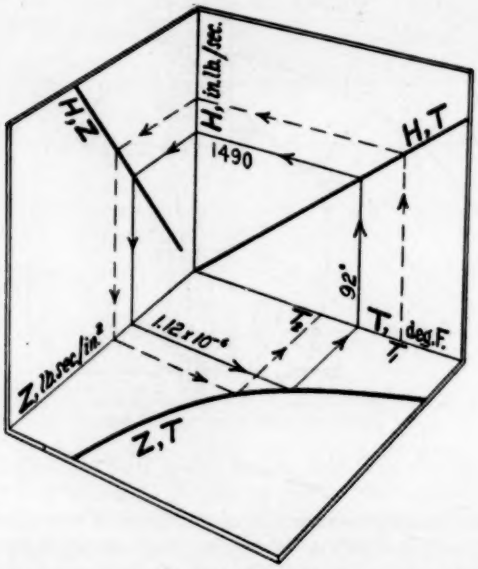
$$f_\infty = \left(\frac{k_2}{\sqrt{k_1}}\right) = \frac{2\pi^2}{P}\left(\frac{D}{C}\right)\sqrt{\frac{aC_0}{B_0}}. \qquad (22)$$

A variety of problems may be solved by the procedure outlined above, since the functions f_1, f_2, and f_3 of Eqs. (6) to (8) are unrestricted. The forms represented by Eqs. (16) to (18) are intended merely as illustrations.

GRAPHICAL SOLUTION.

The principles involved in the simultaneous solution for T, H, and Z are the same whether carried out analytically or

FIG. 2.



Lecture-room model for determining permanent running temperature (T, elevation above room temperature; H, heat generated and transferred per unit time; Z, viscosity).

graphically. The graphical solution is illustrated by Fig. 2, showing a perspective sketch of a model which can be con-

[10] A similar calculation for the maximum load capacity was given in 1914 (Ref. 3 of Section III).

structed from three flat sheets of double corrugated cardboard [11] for lecture table demonstration. The straight line H, T graph corresponding to Eq. (9) is plotted in the right hand upper quadrant; the H, Z graph corresponding to Eq. (10) in the left hand upper quadrant. The Z, T hyperbola of Eq. (11) will be recognized in the lower or horizontal quadrant.

In the graphical method we may find by trial what value of the temperature elevation T satisfies all three relations simultaneously. Starting at random with T_1, follow the broken line up to the H, T graph; horizontally towards the left until it intersects the H, Z line; and from here vertically down, then horizontally to the right until it hits the Z, T curve. The trial diagram is now completed by projecting to the T-axis, where we arrive at some coördinate T_2 evidently less than the initial value T_1. The equilibrium temperature elevation must therefore lie between T_2 and T_1. A very few trials brings us down to the true value, $T = 92$ degrees F.

A more precise solution corresponding to slightly different T, H, Z relations is given by Fig. 3. This chart might have been laid out by cutting the space model along its Z-axis and flattening it down. We now have two Z-axes, one being merely a duplicate of the other turned through an angle of 90 deg. The original relationships are reproduced in the lightly drawn Newton H, T graph; Petroff H, Z graph; and hyperbolic Z, T curve. In addition, there are shown by heavier lines the Lasche H, T curve; McKee H, Z graph; and empirical Z, T curve. The Lasche curve is plotted from Eq. (12). The McKee graph is plotted from Eq. (10) with a correction term $\Delta H = 300$ in. lbs. per sec. based on $\Delta f = 0.002$ (Ref. 15 of Section III). The Z, T curve is reproduced from the curve for Oil A previously mentioned.[12] Applying the trial procedure we find $T = 86$ deg. F., $H = 1940$ in. lbs. per sec., and $Z = 1.21 \times 10^{-6}$ lb. secs. per sq. in. The temperature rise values computed by different methods for the same basic mechanical problem are summarized for comparison in Table 2.

A recent suggestion from Dr. Albert Kingsbury to the author makes it possible to dispense with the trial and error procedure and to obtain the final solution by a single construction. Dr. Kingsbury calls attention to the fact that the H, T and H, Z curves in Fig. 2 are the respective projections of a *space curve* which must also have a projection on the Z, T

[11] Or from the inside corner of a box, with the diagrams pasted on like wall paper.

[12] This curve transforms into a straight line on the A.S.T.M. chart (Ref. 29 of Section I). It represents a typical petroleum oil of about 100 viscosity index, and viscosity 30 centipoises at 100° F.

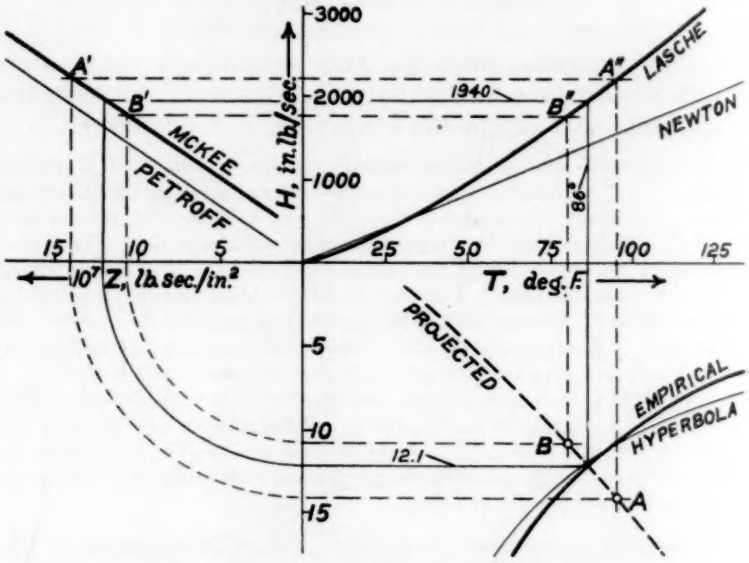
TABLE 2.
Temperature Rise Computations.

Method Used.	Heat Transfer.	Friction Coefficient.	Viscosity Curve.	T, deg. F.
1	Newton	Petroff	Hyperbola	92
2	Lasche	Petroff	Slotte	82
3	Lasche	McKee	Empirical	86

plane. The T-coördinate of the intersection point of this curve with the Z, T curve for the lubricant is the required value of the equilibrium temperature rise.

One method of applying this idea is illustrated in Fig. 3.

FIG. 3.



More precise solution for the permanent running temperature of a bearing.

Draw two or more horizontal lines $A'A''$, $B'B''$, as shown, in order to find two or more points A, B, on the Z, T projection. This will usually be sufficient to locate the intersection point of the two Z, T curves.

The general equation for the Z, T projection of the space curve is given by the simultaneous solution of Eqs. (6) and (7),

$$f_2(Z) = f_1(T). \tag{23}$$

The coördinates of the required intersection point are found analytically by the simultaneous solution of (23) and (8). An example of (23) is given by the equation for the projected curve in Fig. 3,

$$300 + 1.34\,(10)^9 Z = 5.95 T^{1.3}. \tag{24}$$

In this particular case it would have been possible to plot the projected curve directly from Eq. (24) after solving for Z as a function of T, without going through with the graphical construction.

THERMAL EXPANSION.

The principal effect of thermal expansion is to change the clearance, C. Now for any given viscosity the heat generated per unit time is a known function of the clearance, say

$$H = H_0 f_4\left(\frac{C}{C_0}\right). \tag{25}$$

Here H_0 is the value of H at the normal clearance C_0; this, in turn, being the value of C at the room temperature, or other standard temperature, θ_0. In particular, for the full journal bearing following Petroff's law, $H = H_0(C_0/C)$.

Under equilibrium conditions the clearance must be a definite function of the temperature. The relative clearance C/C_0 may then be expressed as a function of the temperature elevation, T; thus

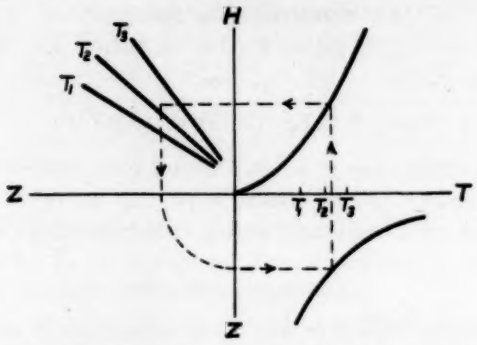
$$\frac{C}{C_0} = f_5(T). \tag{26}$$

But from (7), $H_0 = f_2(Z)$, hence when $f_2(Z)$ and $f_5(T)$ are known, H may be expressed as a known function of Z and T.

The corresponding modification of the graphical method is suggested by Fig. 4. A family of curves for different constant values of T has been drawn in place of the original H, Z graph. The appropriate intersection point on the H, Z plane is found by interpolation, and the solution completed as before.

It remains to inquire into the specific forms which Eq. (26) may assume. Let ϵ_1 and ϵ_2 denote the linear thermal expansivities of the journal and bearing respectively. Ordinarily the journal will be of steel, with a mean expansivity, ϵ_1, of the

FIG. 4.



Graphical solution when the clearance is different at different temperatures.

order of 6.3 parts per million per degree F., depending on the composition and treatment. The bearing housing may be of cast iron, with a corresponding expansivity, ϵ_2, equal to 5.9 neglecting the influence of any thin bronze or babbitt liner. The expansivity of brass or bronze would be nearly twice that of cast iron, and of aluminum still greater.

We may consider two extreme cases, (1) the entire housing at a practically uniform temperature, so that the bearing diameter $D + C$ may be computed on the assumption of unrestricted expansion, corresponding to the temperature elevation T; and (2) bearing expansion negligible, due to the stresses set up. In the first case it may be shown (Ref. 13) that

$$\frac{C}{C_0} = 1 + \left(\frac{D}{C_0}\right)(\epsilon_2 - \epsilon_1)T. \qquad (27)$$

In the second case the desired result may be obtained by setting $\epsilon_2 = 0$ in Eq. (27). In either case, then, (26) may be represented more specifically by (27) with the appropriate values for ϵ_1 and ϵ_2.

As a numerical example, consider a steel journal in a cast iron housing, such that $\epsilon_2 - \epsilon_1 = (5.9 - 6.3) \times 10^{-6}$ per degree F. Then for $T = 86$ degrees and $(D/C_0) = 1000$, Eq. (27) gives $C/C_0 = 1 - .034$, a decrease in clearance of 3.4 per cent. On the other hand if the expansion of the casting is so much restricted by the cooler outside portions that

the effective value of ϵ_2 is reduced by one half, Eq. (27) indicates 33 per cent. decrease in clearance.

That the conditions met in practice do not always fall between the two extremes pictured above is suggested by reports of seizure during the warming-up period (Refs. 2 and 21). In the foregoing analysis end effects have been neglected, and the temperature distribution assumed radially symmetrical. An interesting case of bearing deformation due to temperature inequalities has been described by Karelitz (Ref. 9).

TEMPERATURE DISTRIBUTION IN THE METAL.

Let T denote the temperature elevation above room temperature at any radial distance r from the axis of the bearing. Call r_1 the radius of the bearing surface, and let $T = T_1$ when $r = r_1$. Imagine a series of isothermal surfaces enveloping the bearing surface, and extending out into the metal of the bearing housing at equal temperature intervals. Let dT be the temperature drop between two successive surfaces separated by the distance dn, measured normally; then by Fourier's law the quantity of heat per unit time, $\Delta H'$, crossing any small area ΔA will be proportional to the temperature gradient and given by

$$\frac{\Delta H'}{\Delta A} = -\lambda\left(\frac{dT}{dn}\right), \tag{28}$$

where λ is the thermal conductivity of the metal. Eq. (28) might be taken as the starting point for a general solution of the temperature distribution problem by graphical or other methods.

In the ideal case of a bearing with radial symmetry, long enough to disregard longitudinal flow of heat, (28) reduces to

$$-\lambda\left(\frac{dT}{dr}\right) = \frac{H'}{2\pi r L}, \tag{29}$$

where L is the length of the bearing. Under equilibrium conditions $H' = H$; substituting and integrating,

$$T = T_1 - .37\left(\frac{H}{\lambda L}\right)\log\frac{r}{r_1}. \tag{30}$$

In particular, the temperature at the outer surface of the housing will be expressed by setting $T = T_2$ and $r = r_2$ in (30), where r_2 is the equivalent outside radius. An an application, consider the case in which it was found by Fig. 3 that $H = 1940$ in. lb. per sec., and T (now T_1) $= 86$ deg. F. The length $L = 6$ in., and the bearing radius $r_1 = D/2 = 1.5$ in. The assumption of a housing area 8 times the bearing surface implies an equivalent outside radius $r_2 = 6$ in. Averaging from published tables for λ in lb. per sec. per deg. F. we find for brass, 15; cast iron, 6.4; steel, 5.6; and bronze, 5.2. Adopting the value for cast iron, and substituting into Eq. (30) on the assumption that there are no imperfect thermal contacts between the bearing metal and the cast iron, we obtain for the outside temperature elevation $T_2 = 86 - 11 = 75$ deg. F.

TEMPERATURE DISTRIBUTION IN THE FILM.

The same reasoning applies to the lubricating film except that the quantity of heat per unit time flowing radially outward is not a constant, but depends on the radial distance r. Whereas the metal serves only as a conductor of heat, the film serves both as a conductor and as the medium in which the heat is being generated.

Let ΔF denote the tangential force exerted upon the film by an element of area ΔA of the journal, small enough to be thought of as flat. The stress $\Delta F/\Delta A$ may be represented by S, and the journal radius by r_0. The work done by ΔF in unit time is equal to the product of ΔF by the distance that its point of application moves in unit time, or $U\Delta F$ where U is the linear speed of the journal.

Now consider the action at any surface within the film, for which the radial distance r is greater than the journal radius r_0 but less than the bearing radius r_1. The velocity of this surface is less than that of the journal and may be designated by u. It is equal to U when $r = r_0$ and equal to zero when $r = r_1$. When there is *no pressure gradient* in the film the tangential stress on this surface is equal to that on the journal surface. Consider the work done by the moving body occupying the space defined by radii less than r, upon its surroundings; that is, upon the part of the film lying beyond the radius r. The amount of this work per unit time and for the area ΔA is given by $u\Delta F$. Assuming thermal equilibrium has been reached, the difference between the work done upon the whole film at r_0 and that done upon the portion lying beyond a radius r represents work dissipated into heat between r_0 and r. Thus the heat generated per unit area between

r_0 and r in unit time is given by $(U - u)$ into $\Delta F/\Delta A$, or $(U - u)S$.

If the bearing is long enough relative to its diameter to permit disregarding the longitudinal flow of heat we see that after thermal equilibrium has been set up, there cannot be any further conduction of heat into the shaft. The maximum temperature is at the journal surface, where $r = r_0$. The only flow of heat that we need to consider is directed radially outward. All the heat generated per unit time between r_0 and r is conducted across the isothermal surface at radius r. Hence by Fourier's law

$$-k\left(\frac{dT}{dr}\right) = (U - u)S, \tag{31}$$

where k is the thermal conductivity of the lubricant, and T the temperature elevation at any radius r within the film.

From Newton's law for viscous liquids, changing back from Z to μ for the viscosity notation, $S = -\mu(du/dr)$; substituting into (31), integrating from the fixed radius r_1 where $u = 0$ and $T = T_1$ to the variable radius r where $u = u$ and $T = T$, treating the viscosity and conductivity as constants,

$$T - T_1 = \frac{1}{2}\left(\frac{\mu}{k}\right)\left[2\left(\frac{u}{U}\right) - \left(\frac{u}{U}\right)^2\right]U^2. \tag{32}$$

When the viscosity is uniform and there is no pressure gradient in the direction of motion, as, for example, in the case of a concentric journal bearing, the velocity distribution is given by

$$\frac{u}{U} = \frac{r_1 - r}{r_1 - r_0} = \frac{h - y}{h}, \tag{33}$$

where h is the film thickness and y denotes the distance from the moving surface to any point in the film. Substituting into (32),

$$T - T_1 = \frac{1}{2}\left(\frac{\mu}{k}\right)\left[1 - \left(\frac{y}{h}\right)^2\right]U^2. \tag{34}$$

Thus the temperature distribution is parabolic; and the total drop across the film, obtained by setting $y = 0$, is

$$T_0 - T_1 = \frac{1}{2}\left(\frac{\mu}{k}\right)U^2. \tag{35}$$

It is of interest to note that the temperature drop is independent of the film thickness.

As an example, we have from the previous problem $U = \pi DN = 189$ in. per sec. at 1200 r.p.m. From Fig. 3, the viscosity is approximately $\mu = 1.21 \times 10^{-6}$ lb. sec. per sq. in. Taking for the thermal conductivity of a light mineral oil, at temperatures in the neighborhood of 163° F. (Ref. 11), $k = 0.016$ lb. per sec. per deg. F.; Eq. (35) gives for the temperature drop across the film $T_0 - T_1 = 1.3$ deg. At 100° F. ($\mu = 30$ cp.), $T_0 - T_1 = 4.7$ deg. F. Since the temperature drop is proportional to the square of the surface speed, it must be greater than this for some of the larger diameter journal bearings and thrust bearings.

Although Eqs. (34) and (35) have been deduced on the assumption that the maximum temperature in the film occurs at the moving surface, where $y = 0$ and $u = U$, and that no heat is being conducted across this surface after thermal equilibrium has been reached, a little reflection shows that a more general interpretation is possible. The locus $y = 0$ need not be a material surface. It may be defined as the isothermal surface of maximum temperature. While there can be no heat conduction across such a surface, there may be heat conduction, and a finite temperature gradient, at the surface of the journal or other moving element. In the case of thrust bearings the surface $y = 0$ must be near the middle of the film. The velocity of this surface may be denoted by u_0 and substituted for U in Eqs. (34) and (35).

The earliest publication of Eq. (35) appears to be found in a paper by E. Polhausen, in 1921 (Ref. 7). The same or an equivalent formula has been frequently rediscovered (see, for example, Refs. 15, 18, 22).

In the course of an investigation at Zurich, suggested by Professor Stodola, an expression was derived by Charles Hummel (Ref. 8) for the temperature distribution when there is a pressure gradient in the film. His calculations were based upon a relation equivalent to Lamb's theorem, Eq. 24 of Section I. The necessary expression for the velocity gradient at any fixed value of x was obtained from the hydrodynamic equation

$$\frac{d^2u}{dy^2} = \frac{g}{\mu}, \tag{36}$$

in which g denotes the pressure gradient, $\partial p/\partial x$. Neglecting

side leakage, Hummel obtained an important result which may be written

$$T - T_1 = \frac{1}{2}\left(\frac{\mu}{k}\right)\left\{1 - \eta^2 - \left(\frac{1}{3} - \eta^2 + \frac{2}{3}\eta^3\right)\zeta + \left[\frac{1}{12} - \eta^2\left(\frac{1}{4} - \frac{\eta}{3} + \frac{\eta^2}{6}\right)\right]\zeta^2\right\} U^2 - h(1 - \eta)\left(\frac{\partial T}{\partial y}\right)_0. \quad (37)$$

In this equation η denotes the relative distance across the film, y/h; while ζ is the dimensionless variable $gh^2/\mu U$; and $(\partial T/\partial y)_0$ is the temperature gradient at the surface $y = 0$. If, as before, we take $y = 0$ as a maximum temperature surface, measuring distances and velocities relative to this surface, then $(\partial T/\partial y)_0 = 0$.

For the drop across the film, under the foregoing conditions, putting $\eta = 0$ and $T = T_0$ in (37),

$$T_0 - T_1 = \frac{1}{2}\left(\frac{\mu}{k}\right)\left(1 - \frac{\zeta}{3} + \frac{\zeta^2}{12}\right) U^2. \quad (38)$$

From the fact that ζ appears with an odd, as well as an even exponent, it is evident that the temperature drop will be different on the two sides of any point where the pressure gradient changes sign, for example the point of maximum pressure. This conclusion appears to be in accord with the recent experiments of Nücker (Ref. 19). As a check it will be noted that (37) reduces to (34), and (38) to (35), when the pressure gradient is zero. Thus (34) and (35) are special cases of Hummel's equation.

SOLUTION FOR LARGER TEMPERATURE DIFFERENCES.

The foregoing results are approximations, based on the assumption that the viscosity of the lubricant is not appreciably affected by the temperature differences within the film. It remained for Albert Kingsbury to devise a graphical method for solving the temperature distribution problem when the pressure gradient is negligible, but the temperature drop itself is large (Ref. 24). Kingsbury's method is based upon (1) the empirical curve for k/μ against temperature; (2)

Newton's law of viscosity; and (3) an equation equivalent to (31), with u_0 in place of U.

The results were confirmed experimentally by comparing the calculated and observed torque on an adjustable tapered plug and ring. In this apparatus the clearance could be measured and controlled to a high degree of precision.

The graphical solution is not limited to any particular viscosity-temperature relation. It takes into account, also, the decrease in thermal conductivity of the lubricant with increase in temperature. In the example chosen by Kingsbury to illustrate the method, the surface speed of the journal was equal to 2000 inches per second. Then assuming for the temperatures of the journal and bearing surfaces 140° and 100° F. respectively, it was found that the maximum temperature in the film would rise to 166.6° F., even when using a very light oil (23.2 centipoises at 100° F.). If the shearing stress were computed from the viscosity at the bearing temperature, which is ordinarily the only temperature known, it would be more than two and one-half times the true value. The maximum rate of shear was found to be over three times the minimum, whereas ordinarily, in the absence of a pressure gradient, the rate of shear is assumed uniform throughout the film.

TEMPERATURE-TIME CURVES.

In practice a warming up period of several hours may be required before the permanent running temperature of a bearing is even approximately reached. Apparently no definite generalizations from experiment are as yet available (Refs. 5, 6, 12, 21). The problem might be attacked experimentally with the aid of Eq. (42) of Section III or some further development thereof, utilizing thermally similar models wherever necessary.

In the meantime some assistance might be obtained theoretically by the method of upper and lower limits. The temperature rise T at a given time t must be *at least* as great as would be computed on the assumption that the net accumulated heat is uniformly distributed through the entire mass of the journal, bearing, and housing. This lower limit may be designated by T_L. The true value of T at any instant must be *less* than would be computed by disregarding

all escape of heat from the exterior surfaces, and applying Kelvin's formula for the temperature rise due to a "heat source" distributed over the bearing surface (p. 687 of Ref. 24). If this upper limit is designated by T_U we may plot T_L and T_U against the time t, and can be assured that the true curve must lie somewhere in the region between T_L and T_U. This unknown curve approaches, as an asymptote, a definite horizontal line representing the known equilibrium temperature.

GENERAL SUMMARY.

Now that we have completed our outline of the theory of lubrication [13] it may be worth while to take account of stock briefly. What principles have been established? How can they be applied? What are some of their chief limitations and in what directions will future research be required?

1. Through the contributions of Petroff, Tower, Reynolds, Kingsbury, Sommerfeld, Michell, and others, we have now arrived at a practically useful although still incomplete knowledge of the laws of lubrication. Already the applications of this knowledge have revolutionized the design and operation of machinery; reducing the space occupied and power consumed, and greatly lengthening the life of the bearing surfaces.

2. Petroff recognized bearing friction as a viscosity problem, thereby rendering notable service to the Russian petroleum industry. His equation of 1883, in a simplified form, is still in use for estimating the friction loss of a full journal bearing when operating at high speeds with a light load.

3. Tower's experiments showed the value of profuse lubrication in preventing metallic contact; and through the studies of Osborne Reynolds, led to the principle of the converging film, which underlies the hydrodynamic theory. It is this principle that enables us to understand how the journal of other loaded surface may be floated upon the film of lubricant. Since Tower's experiments were initiated by a research committee of the Institution of Mechanical Engineers, all the good results which have followed from the combined work of Tower and Reynolds may be credited to that organization, and should serve to encourage similar undertakings in the future.

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[13] The remaining lectures were confined to the experimental side of the subject.

4. Kingsbury's experiments on the air-lubricated journal confirmed the hydrodynamic theory, showing clearly that the lubricating action of the film under normal conditions is due to its viscosity, rather than to any chemical characteristics of the particular lubricant. These findings, published in 1897, further stimulated the mathematical development and useful application of the theory.

5. Sommerfeld explained the steps necessary in integrating Reynolds' equation for pressure distribution, and in calculating the equilibrium position of a journal relative to the bearing. These calculations he applied to the half bearing and full bearing, assuming side leakage negligible and the clearance space completely filled with the lubricant even where negative pressures are indicated.

6. Michell solved the mathematical problem of side leakage for the case of flat rectangular surfaces. His results are directly applicable to thrust bearings, and have been further developed by Boswall and others. Michell's solution shows that the load capacity per unit area is decidedly less for bearings of finite width than for the ideal bearings of infinite width previously studied.

7. There followed a long series of attempts by many investigators to solve the side leakage problem for journal bearings. Several approximate methods, notably those of Gümbel, Stodola, and Duffing, based upon arbitrary assumptions, are available; but it remained for Kingsbury to treat this problem with completeness and precision by means of an electrical integration method.

8. In the meantime various details of hydrodynamic theory were gradually being worked out, disregarding the leakage effect; for example, Harrison's solution for compressible lubricants; papers by Stodola and Hummel on critical speeds due to the yielding of the film; studies of inertia pressure by Brillié; and Swift's investigation of the true extent of the film. Howarth developed a graphical method for lubrication calculations, showing how Reynolds' equation might be integrated for any desired bearing arc, both for centrally loaded and offset bearings, and for both fitted bearings and bearings with any stated clearance.

9. Kingsbury determined the optimum conditions for

journal bearings,—the best combination of design factors for either a minimum friction loss, or a maximum load capacity. This problem was solved analytically with the aid of the electrical integration method, in order to take proper account of the leakage effect. Needs published a comprehensive study of the 120° centrally loaded bearing based upon Kingsbury's electrical method; and showing how the side leakage effect varies both with changes in the geometrical factors, and in the operating conditions.

10. The dimensional theory of lubrication provides a means for planning future experiments to determine the laws of lubrication of bearings and other machine elements with a minimum of difficulty. Many scattered experiments have already been published, chiefly on the performance of journal bearings (Ref. 49 of Section II), which should be coördinated as soon as possible by the method of dimensions in order to put our present knowledge of these laws into a more definite and useful form.

11. There is no established theory of imperfect lubrication, applying to such phenomena as wear, seizure, and oiliness, which are important when operating under heavy loads, or when starting and stopping. The nearest approach consists in various hypotheses from which, for the present, only qualitative predictions are to be expected. It seems probable, however, that fresh light may be thrown upon these phenomena by a further development of the hydrodynamic theory, taking into account the imperfect smoothness and rigidity of actual bearing surfaces, together with the increase in viscosity of lubricants under pressure.

12. The importance of considering the temperature conditions in bearings can hardly be overemphasized. Without a knowledge of the equilibrium temperature, the viscosity of the film appearing in the hydrodynamic equations is an unknown quantity. To calculate this temperature we must know the heat transfer law for the bearing. Aside from the experiments of Lasche and of Karelitz relatively little work has been done upon this problem. Now that we understand better how to make use of heat transfer data, more extensive and precise test results will be very much in demand.

In conclusion, we should not think of the lubrication

problem as being limited to the mechanics of the film, but should give equal weight to the properties of the lubricant as affected by temperature and pressure, and to the heat transfer characteristics of the bearing as a whole.

In addition to acknowledgments made in the text, it should be stated that the lectures and discussions in Providence were made possible through coöperation of Dr. William H. Kenerson, Chairman of the Division of Engineering, and James A. Hall, Professor of Mechanical Engineering, Brown University. Similar acknowledgment is due to Professor S. W. Dudley and his associates at Yale. Professor Arthur E. Norton of the Harvard Engineering School has been of frequent help in clearing up some of the difficult points in the theory of the subject. The author's studies over a period of years have been conducted in collaboration with the Special Research Committee on Lubrication, American Society of Mechanical Engineers.

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The Bright Annealing of Non-Ferrous Metals.—Due to the recent great increase in interest in this subject an article by W. Wirt Young in *Industrial Gas* for June 1935 should prove timely. The article is confined to the development of inexpensive bright annealing atmospheres generally prepared from the products of combusion of either natural or manufactured gas. To obtain this atmosphere there are two methods available. The first and more widely used is that of cracking the gas in a generator separate from the annealing furnace and giving it proper treatment. The fundamental apparatus includes a suitable method of mixing gas and air at a constant predetermined ratio, burners of the tunnel type for burning this mixture, a refractory lined generator in which to burn the mixture, a condenser for removing bulk of moisture and sulphur dioxide from burned gas, an iron oxide box and a suitable method of removing traces of moisture down to the equivalent of saturation at 40° F.

The second method consists of taking the products of combustion from a gas fired muffle furnace and, after the proper treatment, using it for the furnace atmosphere. The treatment eliminates moisture and sulphur. The main advantage is fuel economy as the same gas both anneals the metal and furnishes the atmosphere. Gas needed for annealing in excess of atmosphere requirements must be "spilled out."

Mention is made of the satisfactory bright annealing of copper and nickle in a direct fired continuous gas furnace using recirculated products of combusion from a separate generator in the cooling zone. This type of furnace has the advantage of no muffle in the heating chamber, less clean work can be satisfactorily annealed than is possible in electric furnaces, and less products of combusion are needed as none are used in the heating chamber, and those from the cooling chamber are recirculated.

The use of the products of combustion of manufactured gas for a non-oxidizing atmosphere is now definitely out of the experimental stage and in the field of sound commercial application.

R. H. O.

THE END OF AN ERA.

BY

L. K. SILLCOX,

Vice President,

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(Concluded from August issue.)

101. For any speed, V, there is an ideal equivalent superelevation which will maintain the resultant of centrifugal force and car weight normal to the plane of the rails. This superelevation, e, expressed in inches, is approximately defined by the equation:

$$e = 0.00066\ V^2C,$$

where C = degree of curvature as before.

Since any predetermined superelevation is perfectly adapted to a single speed, its selection must, of necessity, compromise the highest anticipated speed and the condition resulting from a train standing or moving very slowly upon the curve. The extent of the resulting unbalance is measured by the variation in pressure exerted upon the right and left rails, respectively. In deriving the proportions which this effect may assume, it is often convenient to consider the factor expressing the proportionate increase in rail load. This value, which may be termed "factor of weight transfer" takes the form,

$$\pm \frac{2he}{G^2},$$

where h = height of center of gravity above rails,
e = superelevation in inches,
G = track gage in inches (56.5 standard).

For a car, standing upon curved and superelevated track, the actual weight born by each rail is greater or less than one half the car weight (neglecting the displacement of the car body due to spring deflection and such outside disturbances as side winds) by an amount equal to the product of one-half

the car weight and the weight transfer factor. The tangent of the angle obtaining between the vertical component and that normal to track surface, is represented by e/G in the above expression, and the equivalent weight transfer factor, when centrifugal force is introduced, takes the same form with proper adjustment for the change in this angle.

102. The three foregoing formulas are derived in Appendix *B* and the effects of the factors upon cars of 35 and 90 tons gross weight are investigated.

103. However powerful the locomotive may be; whatever attention has been accorded locomotive and car design to add to the security of high speed operation; and irrespective of the excellence of track surface and the precision with which superelevation on curves is carried out; no matter how efficient and dependable the system of signalling may be; high speed operation cannot be attempted unless fortified against possible lack of control by the provision of braking capacity commensurate with train weight and with the highest anticipated rate of traveling.

104. The old stagecoach type of brake, manned by an attendant upon each car, fulfilled every need of the earliest railway braking requirements. As train length increased, the need was felt for some arrangement whereby all brakes might be simultaneously applied and many schemes were tried, the purpose of which was to interconnect the braking mechanisms on successive cars, all to be operated from the locomotive. With further development toward longer and heavier trains, manual operation became impractical and steam, vacuum, and air were successively employed to provide the activating force. From this beginning there emerged the straight air brake, quickly followed by the automatic air brake, the latter incorporating principles of operation which have been retained in the design of every subsequent brake type produced since that time.

105. The theory of the automatic air brake is well known. Compressed air is stored under high pressure upon the locomotive, comprising a reservoir for the supply of a lesser quantity upon each car. A communicating pipe extends throughout the train length and pressure is maintained within this air line to which the brake mechanism of each car is

attached. In applying the brakes, the engineman, by manipulation of a conveniently located brake valve handle, permits air to escape from this pipe and, by an ingenious system of pistons and connected multi-port valves, the air reservoir upon each car is connected to its brake cylinder, admitting pressure to extend the piston which, connected through a suitable system of rods and levers, forces the brake shoes against the wheels. Once this method of operation was proven, further development consisted of devising means for improving the control which the engineman might exercise over the functions as they were transmitted through the train.

106. The evolution of the railway train, for both freight and passenger service, has been paralleled by developments in brake capacity and features necessitated by changes observed in method of train operation. While train weight is an important factor in defining the required brake capacity, it is train speed which exerts the predominating influence. In accelerating a train of coupled cars, locomotive effort is employed in creating a store of kinetic energy which the brakes must quickly and safely dissipate whenever occasion arises. Since kinetic energy varies with the weight of the train and the square of its speed, the duty to be performed by the brakes increases four fold where speed is doubled and nine times if speed is trebled. It is for this reason that modern high passenger train speeds have demanded revolutionary changes in brake design and braking practices while the speeds now common in freight service have necessitated the general adoption of a new and improved form of freight car brake to supplant a design which has been in universal and successful use for more than twenty years.

107. If the braking problem were simply that of providing a means for pressing the brake shoes against the wheel treads with a specified force, the condition would not be difficult to obtain. Train braking is, however, so completely encompassed by a series of variables that every conclusion as to what constitutes the most desirable braking characteristics under any specified condition of train consist, weight, and speed represents a carefully selected compromise involving stopping distance, security from the hazard of

sliding wheels, safety, and comfort to passengers or protection to lading.

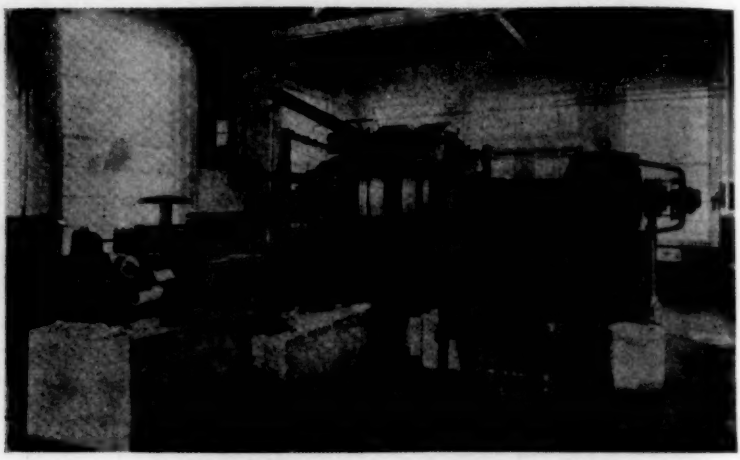
108. Until the advent of trains designed to regularly operate at speeds exceeding one hundred miles per hour, entirely satisfactory stops were obtainable by the exercise of the engineman's judgment as to how great a retarding force might be impressed without stopping the rotation of the wheels and causing them to slide. As long as this method of operation is followed, the minimum safe stopping distances are not realized and slid flat wheels are not uncommon in passenger service where sufficient braking effort is obtainable to cause wheel sliding. Signal spacing on all lines has been arranged to accommodate trains of conventional type, braked in accordance with a schedule to which all railways have adhered for many years. As the kinetic energy possessed by a train varies with the square of its speed, so does the stopping distance vary with the square of the initial speed, whatever it may be, assuming a constant retardation force to be active in all cases. However, since the new trains, intended to operate at twice the speed of the conventional types supplanted, must require no greater distance in which to stop, it is necessary that they be equipped to receive four times the retarding force and this must be impressed without wheel sliding and without discomfort to passengers.

109. The condition under which wheel sliding can occur is not difficult to define in general terms but it is, in view of the meagre data available, very difficult to assign a value to the variables which must be considered. Throughout every brake stop there are two couples acting upon the wheels, one tending to maintain wheel rotation, the other tending to prevent it. Each represents a force acting at the end of a lever arm equal to one-half the wheel diameter. On the one hand there is the brake shoe pressure, multiplied by the coefficient of brake shoe friction, constituting a force at the periphery of the wheel tending to arrest rotation. On the other hand, there is the weight upon the wheel times the coefficient of wheel-rail adhesion which serves to prevent wheel sliding. This latter force must exceed the former to insure stability of rotation of any braked wheel, the problem resolving itself into a consideration of forces only since each combines with the same lever arm to form a turning couple.

110. In the measurement of the force with which the brake shoe presses against its wheel, there is a known relationship existing with respect to car weight under a stated condition of pressure within the brake cylinder. For example, an emergency braking ratio of 150 per cent. may be specified for a passenger car of eighty tons light weight with a brake cylinder pressure of one hundred pounds per square inch. This would be interpreted to mean that the force exerted by the brake cylinder piston, multiplied by the ratio of the leverage system whereby the brake cylinder force is transmitted to the shoes, is such that the combined pressure of all shoes is equivalent to 150 per cent. of car weight or, in the case of an eighty ton car, 240,000 pounds. With the car supported upon twelve wheels, the brake shoe pressure per wheel would be 20,000 pounds and, with two brake shoes per wheel, each shoe would receive a pressure of 10,000 pounds. Actually, the brake shoe pressure would be five to fifteen per cent. less than that theoretically derived in the above manner since there is some loss suffered in transmission of brake cylinder force to the shoes. Since the amount of this loss is not readily determinable, it is frequently combined with the variable coefficient of brake shoe friction value to constitute a composite factor by which theoretical brake shoe pressure is multiplied to define the actual retarding force effective upon the wheel.

111. There has been very little concern registered in regard to just what value the coefficient of brake shoe friction assumes under various conditions of speed, brake shoe pressure, size of brake shoes, and their composition for the reason that tolerable results have been obtained through adherence to practices developed through years of experience. Now, however, since the demand for maximum braking forces has arisen almost overnight, there is a very real need for complete and dependable information regarding the performance of brake shoes on the types of wheels in current use, both chilled cast iron and steel.

112. Brake shoe testing laboratories have been set up at various locations throughout the country for the purpose of determining the properetis of brake shoes and wheels and for the establishment of the retarding forces active under specified



Brake shoe testing laboratory, Purdue University.

conditions of speed and pressure. Since the fact has long been recognized that brake shoes are most effective and subject to least wear when applied with moderate forces and since entirely satisfactory train stops have been obtainable under such conditions, very little data have been assembled to derive the maximum limit of shoe pressure although such tests as have been made, both in road service and in laboratories, indicate a value of approximately 18,000 pounds per standard cast iron shoe as the maximum which can be practicably applied. This is equivalent to a unit pressure of approximately five hundred pounds per square inch of contact area. Analyses of brake shoe test data have definitely established certain relationships which unerringly prevail under all conditions. For instance, it is known that the coefficient of brake shoe friction decreases as brake shoe pressure increases and there is evidence to show that, at least within the pressure range of six to twelve thousand pounds pressure per shoe, values below those at which major changes occur within the shoe structure, the coefficient of friction varies directly with shoe pressure to some fractional power, the value of which may be taken to be approximately 0.47 with a reasonable degree of assurance. The variation of the coefficient of brake shoe friction with speed is even more difficult to define

and is less reliably obtained although as speed is increased, the coefficient of brake shoe friction is diminished but to what extent is not definitely known.

113. In the attempted determination of the coefficient of rail-wheel adhesion by observation of the point at which wheel sliding occurs during road trials, there are four major conditions involved which render the derivation of this factor especially difficult. First, in order that the force tending to rotate the wheel at the point of sliding may be known, it is essential that the opposing force also be known and until instantaneous values of the coefficient of brake shoe friction are established with certainty, not much can be accomplished in the direction of fixing the coefficient of rail adhesion. Then there is to be considered the adhesive weight resting upon the wheels and this is not constant since there is known to be a transfer of static weight from truck to truck and axle to axle of the same truck, the car body, being spring mounted, is subject to vertical oscillation which results in instantaneous weight values alternately above and below the average, and a lateral transfer of weight is constantly recurring due to the interaction of coupled cars and the pressure of wheel flanges against the rails. A third variable is observed in the condition of the rail surface since moisture, frost, or other deposits have a pronounced effect upon its adhesive properties. Fourth, there is the area of contact between wheel and rail to be taken into account since the greater the contact area, the more stable is the wheel against sliding, a fact that has been thoroughly demonstrated by observation of new and worn wheels on new or well mated rail heads. There is nothing to indicate any variation in the coefficient of rail adhesion with the speed at which wheels pass over the track and inasmuch as the wheel rail contact is normally static as long as the wheel continues to rotate, the rate of traveling can be neglected in any consideration of rail adhesion. Speed does, however, influence the adhesive weight variation and for this reason the permissible retarding force may be limited by speed to a value smaller than that which might otherwise be safely impressed.

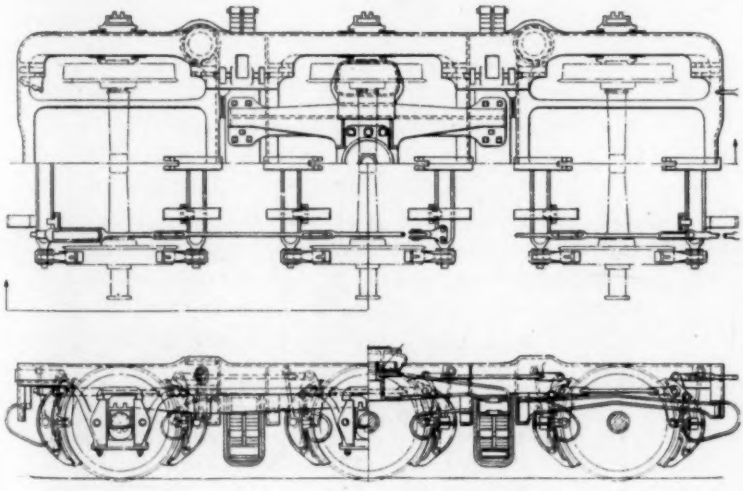
114. In the face of all these unknowns, it has been necessary to arrange a braking system competent to take advan-

tage of every pound of retarding force reliably obtainable, to remove all uncertainties respecting its repeated operation in a predetermined fashion, and to impress the retarding force in such a way that the patrons of the new, high speed, light weight trains will suffer no discomfort at any point during stops from high speed. First it was necessary to assemble all available data which might be productive of important information regarding the proper values to assign the coefficient of brake shoe friction. Recourse had to be taken to intelligent extrapolation of the dependable results recorded in a rather limited range of pressures and speeds. It was known that a rail adhesion value of 0.25 is generally obtainable under any rail condition by the proper use of sand. Repeated observations had disclosed the fact that persons are not conscious of very high rate of retardation if maintained constant throughout the stop. The objectionable and abrupt stop frequently experienced with conventional equipment was properly attributed to a rapid rise in the value of the coefficient of brake shoe friction as speed decreased. Similarly, the not infrequent sliding of wheels at low speeds was assigned the same cause.

115. Basing judgment upon these facts, there has been developed a brake for ultra high speed service which employes a total brake shoe pressure higher in relation to train weight than any which has been attempted before in trunk line service. Automatic sanding is provided. The maintenance of a constant maximum retardation rate is effected by introducing an automatic system of brake cylinder pressure control employing a principle never before commercially applied to train braking. By the use of this device, to which, in its initial application, was given the trade name, Decelakron, the inertia of a weight, mounted on frictionless bearings, was employed to measure the retardation rate and at the same time to admit pressure to or release pressure from the brake cylinders in such a manner that a uniform retardation rate would be maintained. Thrusting forward against the resistance of a carefully calibrated spring when the retardation rate attains too high a value, the weight actuates a valve to relieve a part of the brake cylinder pressure, guarding against wheel sliding and discomfort to passengers in one operation.

To prevent an abrupt stop, practically all of the brake cylinder pressure is automatically exhausted an instant before the train comes to rest.

116. Improved braking characteristics, alone, obtained in the manner just described, cannot be entirely effective under all circumstances in contributing to the shortest possible safe stops from very high speeds. Mention has been made of the coefficient of brake shoe friction, variable with pressure and, with any conventional foundation brake gear arrangement, it not infrequently happens that the permissible brake shoe pressure is exceeded before the maximum retardation rate is obtained. Thus, if available data suggest the use of a brake shoe pressure equivalent to twice car weight, but the adoption of such a pressure exceeds the limiting value of 18,000 pounds per shoe, the retardation rate must be fixed at the value set by the consideration of shoe pressure, sacrificing stopping distance to that extent if conventional brake gear is employed. This necessity has been responsible for the development of a new form of foundation brake gear which employs two or four shoes to replace the one or two common with the familiar arrangements of single or clasp brake type. Not only is a brake rendered less efficient by the pronounced decrease in the value of the coefficient of brake shoe friction when unit pressures in excess of five hundred pounds per



square inch are employed but higher pressures, applied over any prolonged period of contact such as obtains during stops from high speed, frequently result in a complete failure of the brake shoe itself, the metal becomes plastic and wastes away rapidly without performing the requisite retarding action. It is expected that, by doubling brake shoe contact area in the manner illustrated, difficulty arising from pressure limitations will be entirely eliminated.

117. Thus, by steadfastness in study and research, anticipating the demands of the future and preparing for them, the major obstacle to pronounced acceleration of train speeds was surmounted before the adoption of such speeds was contemplated—an illustration of the coöperative spirit which pervades the railway and allied industries and offers assurance of the sustained resourcefulness of the railways in meeting the changing conditions which now confront them.

118. Of all the improvements in operating efficiency and modernization of equipment which are engaging the attention of the railways, the public appears to have accepted weight reduction and streamlining alone as features of sufficiently revolutionary character to attract its interest. This selection does not suggest relative importance. Other factors may successfully rival the effect of combined weight reduction and streamlining, carried to any practical degree, upon railway net income. But weight reduction and streamlining do command popular attention. They are visibly evidenced. New materials, car surfaces free from projecting rivet heads, and new shapes impress themselves upon the attention of all who witness these new designs. The adoption of the superheater and transition to the type E design marked advance in the direction of economical steam locomotive operation which any degree of streamlining can scarcely be expected to equal until unprecedented speeds become the rule. A comprehensive study of the modern steam locomotive provides unlimited material for a helpful analysis of what has been accomplished to permit faster and finer service at decreasing unit cost. Passenger riding comfort, assisted by improved spring arrangements and truck design, heavy rail sections, stronger track structure and improved maintenance standards carried out with decreasing costs, invite

attention. Air conditioning of passenger carrying cars and new methods of refrigeration and temperature control for freight train cars occupy an important position in modern railroading. The rapid extension of practices designed to improve terminal efficiency and to reduce total transport time comprises a complete study in itself. There are an unlimited number of active projects, each one of which merits most thorough examination by those who are interested in the prosperity of our railways and the diligence with which they are attacking the problems which are becoming constantly more onerous. The fact that such changes go on unnoticed by any except those most closely associated with railway mechanical problems strictly limits the interest which they arouse. If the public could appreciate the revolutionary changes which have escaped its attention in recent years, it would be far less critical of the railways.

119. Power and time, the two components of mechanical work are, in human terms, only functions of purpose. They have no more value, apart from human purpose, than has a brick which has been carelessly dropped into the sea. The increase of power and the acceleration of movement which has obtained in this generation have become ends in themselves: ends that justified themselves apart from their human consequences. The industry which took the greatest advantage of this process was not that of manufacturing but that of transport and its success is all the more remarkable because so little of the earlier technique of the stagecoach could be carried over into the new means of conveyance. The railway was the first industry to benefit by the use of electricity: for the telegraph made long distance signalling and remote control possible; and it was in railway work that the routing, timing, and inter-relationship of the various parts of production took place more than a generation before similar tables, schedules, and estimates made their way into industry as a whole. With the development of the necessary devices to sustain regularity and safety, from the automatic air-brake, automatic coupler, power actuated switch, and electro-mechanical signal system, to the perfection of a routing plan for passenger, express and freight traffic, moving at varying rates of speed and under constantly and widely modifying

conditions of weather, density of traffic, and profile of roadway, from point to point within the social limitations of the period, the railway was both the most characteristic and the supreme technical and administrative achievement of the nineteenth century.

120. The advance of rapid transport occasioned a change in the method of time-keeping. Sun time, which varies a minute every eight miles one travels from east to west, could no longer be practicably observed. Instead of a local time, derived from the sun's position, it became necessary to impose conventional time belts and to change abruptly by a whole hour as one passed from one uniform time district to the next. Standard time was imposed by the transcontinental railways themselves in 1875, ten years before the regulations for standard time were officially promulgated at a World Congress. Thus, mechanical time became a matter of routine; the acceleration of the tempo became a new objective for industry and national advance. To quicken movement through space, regardless of whether the traveler journeys for pleasure or profit, has become the goal toward which all transport development has pressed. Power, however, cannot be dissociated from its counterpart in work, namely, time. The primary use of power is found in its ability to decrease the time during which any given quantity of work can be performed. That much of the time so saved during train movements has long been wasted away in disordered schedules and in delays arising from lack of coördinated administration in the handling of traffic from initial receipt to final destination, is a fact which has diminished the efficiency of the program and was never seriously realized until competitive forms of transport brought into play wide challenges against the monopolistic traffic policies of the railways. Time, in short, has finally become a commodity in the sense that money has long since been recognized as a commodity.

121. In the progress here recorded is written the lives of countless men who, through sacrifice, courage, conviction, and the opportunity and encouragement that has been accorded them, have brought this vast, complex, transport system into being. There results a higher standard of life, social and economic, and a broader opportunity in life for countless millions.

122. There is involved the possibility of still higher standards of living. There is also involved a still broader opportunity for all. Heretofore all our transportation problems have been settled under political or community pressure. The present situation must be dealt with from the standpoint of sound national economics and from no other angle. The contribution of our railways to the development of the country as a whole has been conspicuous; they should be preserved in a form which will enable them to continue that contribution and to be, if it is possible to make them, a potent factor in the restoration of prosperity in this country and in the relief of its tax-payers. This, if accomplished, must be through a method of operation which, while preserving to the country all its essential transport facilities, will still provide them in a manner that will add to the prosperity of every citizen by reducing his tax burden. Our transport problem can be comprehended fully only after a study has been made of the background from which it has emerged in our time in a startling and menacing form.

123. One of the lessons learned from the depression is that, throughout the world and on this continent particularly, we have gone ahead building up new forms of transportation and extending old forms without stopping to consider the relation which each must bear, one with another, or the relation of each to the whole economic structure. As a result, we have acquired an overhead of staggering dimensions. There may be some truth in the old saying that competition is the life of trade, but, carried to extremes, competition, by placing too great a burden on trade, may become its most deadly enemy.

124. A survey of many branches of useful endeavor upon transport projects discloses the fact that great thought and effort is being expended and real progress effected toward what we might call bigger and better things in the not distant future. These elements of advance affect all phases of our daily lives; they indicate still broader opportunities ahead; they demonstrate that the world about us is in no way static.

APPENDIX *A*.

COMPARATIVE HORSEPOWER REQUIREMENTS.

3-Car Train Units.

The comparative horsepower requirements here calculated are carried out on 3-car train units comprised as follows:—

Item.	(*a*) Ordinary Weight, Conventional Design, Passenger Train Cars.	(*b*) Light-Weight, Conventional Design, Passenger Train Cars.	(*c*) Light-Weight, Streamline, Articulated, Passenger Train Cars.
Light-Weight per car, tons...	70*	33.33†	—‡
Light-Weight per train, tons..	210	100.00	100.00
Frontal Area, sq. ft.....	115	100	85

* Each car mounted on two 6-wheel trucks or six 6-wheel trucks per train.

† Each car mounted on two 4-wheel trucks or six 4-wheel trucks per train.

‡ Each train mounted on four 4-wheel trucks or four 4-wheel trucks per train.

Train Resistance:

The train resistances of all three types of trains are calculated from the Davis (General Electric Co.) formulas. For the conventional trains, the train resistance formulas for multiple-unit trains are used, treating three-car trains as comprising one leading car and two trailers. For the streamlined train, the whole train is considered as one car, its resistance being figured on the basis of the formula for leading car of the multiple-unit train but with a modified coefficient of air resistance.

The formulas are:

For Conventional Train

$$\text{Leading Car } R = 1.3 + \frac{29}{W} + 0.045V + \frac{0.0024AV^2}{WN};$$

$$\text{Trailing Car } R = 1.3 + \frac{29}{W} + 0.045V + \frac{0.00034AV^2}{WN}.$$

For Streamlined Train

$$R = 1.3 + \frac{29}{W} + 0.045V + \frac{0.001AV^2}{WN},$$

where R = resistance, in pounds per ton,
W = average weight per axle, in tons,
V = speed in miles per hour,
A = frontal (sectional) area, in square feet,
N = number of axles.

(*a*) *Ordinary Weight, Conventional Design Train:*

$WN = 70$ tons, $N = 6$, $W = 11.67$ tons, $A = 115$ sq.ft.,

$$R = 1.3 + \frac{29}{11.67} + 0.045V + \frac{0.0024 \times 115 \times V^2}{70},$$

$R = 3.79 + 0.045V + 0.0039V^2$ for Leading Car,
$R = 3.79 + 0.045V + 0.00056V^2$ for Trailing Cars.

Speed m.p.h.	Resistance Leading Car.		Trailing Car.		Total Train Resistance, Lb.	Horsepower Required.
	Lb. per ton.	Lb.	Lb. per ton.	Lb.		
0	3.79	265	3.79	530	795	0
10	4.63	325	4.30	602	927	24.7
20	6.05	424	4.92	698	1,122	60.0
30	8.65	606	5.64	790	1,396	111.7
40	11.83	830	6.49	910	1,740	185.5
50	15.79	1,105	7.44	1,042	2,147	286.0
60	20.53	1,437	8.51	1,190	2,627	420
70	26.05	1,823	9.68	1,356	3,179	593
80	32.35	2,260	10.97	1,535	3,795	810
90	39.43	2,760	12.38	1,735	4,495	1,080
100	47.29	3,310	13.89	1,945	5,256	1,395

(*b*) *Light-Weight, Conventional Design Train:*

$WN = 33.33$ tons, $N = 4$, $W = 8.33$ tons, $A = 100$ sq.ft.,
$R = 4.8 + 0.045V + 0.0072V^2$ for Leading Car,
$R = 4.8 + 0.045V + 0.0010V^2$ " Trailing Cars.

Speed m.p.h.	Resistance Leading Car.		Trailing Car.		Total Train Resistance, Lb.	Horsepower Required.
	Lb. per Ton.	Lb.	Lb. per Ton.	Lb.		
0	4.8	160	4.8	320	480	0
10	5.97	199	5.35	357	556	14.8
20	8.58	286	6.10	406	692	36.9
30	12.63	421	7.05	470	891	71.3
40	18.12	604	8.20	546	1,150	122.8
50	25.05	835	9.55	636	1,471	196
60	33.42	1,114	11.10	740	1,854	297
70	43.23	1,441	12.85	855	2,296	428
80	54.48	1,816	14.80	987	2,803	598
90	67.17	2,239	16.95	1,130	3,369	808
100	81.30	2,710	19.30	1,286	3,996	1,066

(*c*) *Streamlined, Articulated Train:*

$WN = 100$ tons, $N = 8$, $W = 12.5$ tons, $A = 85$ sq.ft.,
$R = 3.62 + 0.045V + 0.00085V^2$.

Speed m.p.h.	Train Resistance.		Horsepower Required.
	Lb. per Ton.	Lb.	
0	3.62	362	0
10	4.16	416	11.1
20	4.86	486	25.9
30	5.74	574	46.0
40	6.78	678	72.4
50	8.00	800	107
60	9.38	938	150
70	10.94	1,094	204
80	12.66	1,266	270
90	14.56	1,456	350
100	16.62	1,662	444

Summary of Horsepower Requirements:

Horsepower Necessary for 3-Car Trains on Level Tangent Track.

Speed m.p.h.	Ordinary-Weight Conventional Train.	Light-Weight Conventional Train.	Light-Weight Streamlined Articulated Train.
0	0	0	0
10	25	15	11
20	60	37	26
30	112	71	46
40	186	123	72
50	286	196	107
60	420	297	150
70	593	428	204
80	810	598	270
90	1,080	808	350
100	1,395	1,066	444

The horsepower relationships are indicated on the chart, page number 239 of the text.

Saving in Power:

By comparing the horsepower requirements of the ordinary-weight conventional train with that of the streamlined train of light-weight construction, the saving in horsepower due to both the reduction in weight and streamlining may be computed. The saving due to weight reduction alone may be secured by comparing the horsepower requirements of the ordinary-weight and the light-weight conventional

trains. The saving in horsepower requirements due to the effect of streamlining alone may be computed by comparing the light-weight streamlined train with the conventional light-weight train. The saving in horsepower and the percentages, thereof, of saving are computed and tabulated as follows:

Comparative Horsepower Requirements on Level Tangent Track.

Speed m.p.h.	Streamlined vs. Ordinary-Weight Conventional Train.		Streamlined vs. Light-Weight Conventional Train.		Ordinary vs. Light-Weight Conventional Train.	
	Saving.	Per Cent.	Saving.	Per Cent.	Saving.	Per Cent.
20	34	56.8	11	29.7	23	38.4
30	66	59.0	25	35.2	41	36.6
40	114	61.2	51	41.5	63	33.9
50	179	62.6	89	45.5	90	31.7
60	270	64.3	147	49.5	123	29.3
70	389	65.7	224	52.4	166	27.9
80	540	66.6	328	54.9	212	26.2
90	730	67.6	458	56.7	272	25.2
100	951	68.2	622	58.4	329	23.6

The percentage of saving in each case is plotted on preceding page 240.

Effect of Grade:

When the trains are operated on grade, an additional element of resistance is introduced and its magnitude is in the order of 20 lb. per ton weight for each one per cent. of grade. The necessary horsepower required to overcome this grade resistance is, consequently, equal to

$$HP \text{ (grade)} = \frac{20G \times W \times V}{375}$$

where G = upgrade or plus grade, in per cent.,
W = weight of train, in tons,
V = speed, in m.p.h.

Since the additional horsepower required to overcome the grade resistance is directly proportional to the weight of the train, it is apparent that, at the corresponding speeds,

1. The increase in horsepower requirement for a light-weight train is only a small proportion of the increase in

horsepower for a corresponding ordinary or heavy-weight train, the proportion being the same as the ratio of the train weights, and

2. The increase in horsepower requirement for a train of a given weight is not affected by the form of the train; that is, streamlined or conventional.

It follows, then, that *based upon percentages,*

1. For light-weight versus ordinary or heavy-weight trains, both types having the same general form, that is conventional or streamlined, the relative saving in horsepower is greater on grade than on level track.
2. For light-weight streamlined versus ordinary or heavy-weight conventional trains, the proportionate saving in horsepower is less on grade than on level track.
3. For trains of the same weight, streamlined versus conventional, the percentage of saving in horsepower is less on grade than on level track.

The above conclusions are developed fully in the following examples, in which an upgrade or plus grade of 1.0 per cent. is introduced, as follows:

Upgrade or Plus Grade of 1.0 per cent.:

Grade resistance = 20 × 210 = 4,200 lb. for the ordinary or heavy-weight train.

Grade resistance = 20 × 100 = 2,000 lb. for the two light-weight trains.

Horsepower required to overcome grade resistance:

Speed m.p.h.	Horsepower. Ordinary or Heavy-Weight Trains.	Horsepower. Light-Weight Train.
0	0	0
10	112	53.3
20	224	106.7
30	336	160.0
40	448	213.3
50	560	266.7
60	672	320.0
70	784	373.3
80	896	426.7
90	1008	480.0
100	1120	533.3

The total horsepower required on an upgrade or plus grade of 1.0 per cent. at the various speeds is as follows:

Horsepower for 3-Car Train or Plus 1.0 Per Cent. Grade.

Speed m.p.h.	Ordinary or Heavy-Weight Conventional Train.	Light-Weight Conventional Train.	Light-Weight Streamlined Train.
0	0	0	0
10	134.7	68.1	64.4
20	284.0	143.6	132.6
30	447.7	231.3	206.0
40	633.5	336.1	285.7
50	846.0	462.7	373.7
60	1092.0	617.0	470.0
70	1377.0	801.3	577.3
80	1706.0	1024.7	696.7
90	2080.0	1288.0	830.0
100	2515.0	1599.3	977.3

The saving in horsepower is as follows:

Comparative Horsepower Requirements on an Upgrade or Plus Grade of 1.0 Per Cent.

Speed m.p.h.	Streamlined vs. Heavy-Weight Conventional Train		Streamlined vs. Light-Weight Conventional Train.		Ordinary or Heavy-Wt. vs. Light-Weight Conventional Train.	
	Saving.	Per Cent.	Saving.	Per Cent.	Saving.	Per Cent.
20	151.4	53.4	11.0	7.6	140.4	49.4
30	241.7	54.0	25.3	10.9	216.4	48.3
40	347.8	55.0	50.4	15.0	297.4	47.1
50	472.3	55.9	89.0	19.3	383.3	45.3
60	622.0	57.0	147.0	23.8	475.0	43.5
70	799.7	58.1	224.0	28.0	575.7	41.8
80	1009.3	59.2	328.0	32.0	681.3	39.8
90	1250.0	60.2	456.0	35.6	792.0	38.1
100	1537.7	61.1	622.0	38.9	915.7	36.4

The percentages of saving in horsepower on an ascending grade or plus grade of 1.0 per cent., are plotted on page 241.

APPENDIX *B.*

The relative safety of trains comprising light-weight and conventional or heavy-weight equipment, respectively, may be approximated in the manner outlined below:

(1) *Tendency to Overturn on Curved Track:*

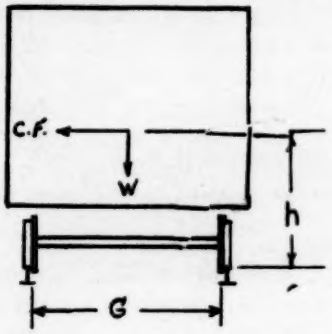
Let W = weight of equipment, in tons,
V = speed, in m.p.h.,

v = speed, in ft. per sec.,
r = radius of curve, in ft.,
$C.F.$ = centrifugal force, in lb.

$$C.F. = \frac{2000\ W}{g} \times \frac{v^2}{r} = \frac{2000\ W}{32.2} \times \frac{1.467^2 \times V^2}{r},$$

$$C.F. = 134 \frac{WV^2}{r}. \tag{1}$$

Let h = height of centre of gravity above top of rail, in inches,
G = gage of rails, in inches or 56.5 in. Std.



$$\text{Turning Moment} = C.F. \times h = \frac{134 WV^2 h}{r} \text{ in lb.},$$

$$\text{Resisting Moment} = 2000W \times \frac{G}{2} \text{ in lb.}$$

At the point of overturning the resisting moment must equal the turning moment, or

$$\frac{134 WV^2 h}{r} = \frac{2000 WG}{2}.$$

Solving for V^2,

$$V^2 = 421.6 \frac{r}{h}. \tag{2}$$

Let C = Degree of curvature, then

$$C = \frac{5730}{r}, \text{ or } r = \frac{5730}{C}.$$

Substituting the value of r in Eq. (2),

$$V^2 = 421.6 \times \frac{1}{h} \times \frac{5730}{C} = \frac{2{,}415{,}768}{Ch}. \tag{3}$$

Equation (3) may be used to solve the relation between the overturning speed V and the curvature for any given height of centre of gravity h.

For 35 ton cars, with $h = 46.5$ in.

Equation (3) becomes $V^2 = \frac{51{,}952}{C}$. (3*a*)

For 90 ton cars, with $h = 57$ in.

Equation (3) becomes $V^2 = \frac{42{,}382}{C}$. (3*b*)

Curvature—Degrees.	Speed at which Equipment may be Overturned.			
	35-ton Cars.		90-ton Cars.	
	V^2.	V m.p.h.	V^2.	V m.p.h.
1	51,952	227.9	42,328	205.7
2	25,976	161.1	21,164	145.5
3	17,317	131.6	14,109	118.5
4	12,988	113.9	10,582	102.8
5	10,390	101.4	8,466	92.0
6	8,659	93.1	7,055	84.0
7	7,422	86.1	6,047	77.7
8	6,494	80.6	5,291	72.7
9	5,772	76.0	4,703	68.6
10	5,195	72.1	4,233	65.1
15	3,463	59.0	2,822	53.0
20	2,598	50.9	2,116	46.0

The speeds at which the equipment may be overturned on curved track with no superelevation, as shown above, are plotted against curvature in the figure, page 248. This chart and the table from which it is derived are helpful only in that they indicate relative tendencies but cannot be accepted as defining the limiting safe speeds for operation on curves. It is shown, however, that weight is not a factor in the stability of equipment.

In the above case, the effect of superelevation, generally practiced on curves, is not considered. In order to maintain speed on curves, the outer rail may be raised above the inner to balance the centrifugal force created by the curvature. The amount of superelevation required to accommodate the

curvature and the operating speed desired, may be expressed by the equation:

where $e = 0.00066V^2C$ (4)

e = superelevation, in inches

V = speed, in m.p.h.

C = degree of curvature.

Equation (4) is derived in the following manner:

Referring to the accompanying sketch,

$$BD = \text{Centrifugal Force} = 134\frac{WV^2}{r}.$$

$$C.F. \text{ acting along } BA = 134\frac{WV^2}{r}\cos\alpha.$$

Weight acting along $BC = 2000W \sin\alpha$.

Equating $BA = BC$, we have

$$\frac{134WV^2}{r}\cos\alpha = 2{,}000W\sin\alpha,$$

$$\tan\alpha = 0.067\frac{V^2}{r}.$$

Superelevation, $e = G\sin\alpha$.

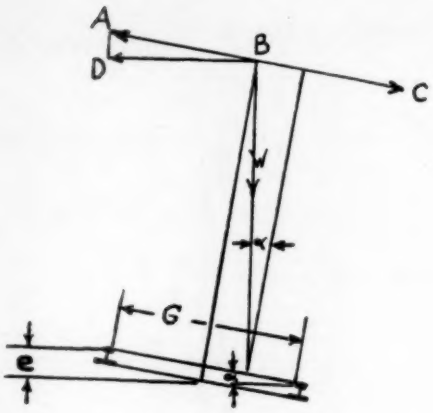
By taking $\tan\alpha = \sin\alpha$ for small angles of α, we have

$$e = G\sin\alpha = G\tan\alpha = 0.067G\frac{V^2}{r};$$

substituting $r = \frac{5730}{C}$,

$$e = 0.00066V^2C.$$

Here, again, it is observed that the proper amount of superelevation is a function of the speed and curvature only, being independent of the weight of the vehicle. In addition, there is only one proper superelevation for each combination of speed and curvature. In actual practice, the superelevation has to be a compromise to care for high as well as low speed trains. This immediately leads to a consideration of lateral weight transfer of the vehicle on a curve. When the vehicle is operated at a speed lower than that for which the superelevation is provided, the weight transfer is from the outer rail to the inner rail. On the other hand, when the speed is greater than that for which superelevation is ideally



adjusted, the weight transfer is from the inner rail to the outer rail.

(2) *Lateral Weight Transfer on Curves:*

Case No. 1: Lateral weight transfer, owing to super-elevation, of the vehicle when it is at rest, or at low speeds, when there is practically no centrifugal force.

Referring to the accompanying diagram,

Weight W acts along BK.

R_0 = Rail pressure at E (outer rail) $= W \times \frac{KF}{G}$,

R_1 = Rail pressure at F (inner rail) $= W \times \frac{KE}{G}$.

Since $KF = \frac{G}{2} - KN$, and $KE = \frac{G}{2} + KN$

and $KN = h \tan \alpha$, and $\tan \alpha = \frac{e}{G}$,

then $KN = h \times \frac{e}{G}$.

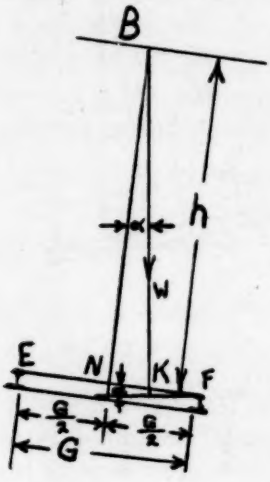
Thus, we have

$$R_0 = \frac{W}{G}\left(\frac{G}{2} - h \times \frac{e}{G}\right) = \frac{W}{2}\left(1 - 2\frac{he}{G^2}\right) \qquad (5a)$$

$$R_1 = \frac{W}{G}\left(\frac{G}{2} + h \times \frac{e}{G}\right) = \frac{W}{2}\left(1 + 2\frac{he}{G^2}\right). \qquad (5b)$$

The weight transfer factor is

$$\mp \frac{2he}{G^2},$$



where h = height of centre of gravity above top of rail, in inches,

e = superelevation of rail, in inches,

G = gage of track, in inches or 56.5 in. for Standard Gage.

The (−) sign applies to the outer rail and the (+) sign applies to the inner rail. The weight transfer factor is again independent of the weight of the vehicle, but, on the other hand, is directly proportional to the height of the centre of gravity. It follows that, regardless of the weight of the vehicle, the lower the centre of gravity of the vehicle, the less is the weight transfer on curved track provided with superelevation, when the vehicles run at a speed lower than that intended for the assigned superelevation. In this particular case,

For 35-ton cars, $W = 35$; $h = 46.5$, $G = 56.5$ and a superelevation of 6 in. is assumed.

$$\frac{2he}{G^2} = 2 \times \frac{46.5 \times 6}{56.5^2} = 17.4 \text{ per cent.}$$

$$\text{Weight on Outer Rail} = \frac{35}{2}(1 - .174) = 14.5 \text{ tons},$$

$$\text{Weight on Inner Rail} = \frac{35}{2}(1 + .174) = 20.5 \text{ tons}.$$

For 90-ton cars, $W = 90$; $h = 57$; $G = 56.5$ and $e = 6$,

$$\frac{2he}{G^2} = 2 \times \frac{57 \times 6}{56.5^2} = 21.4 \text{ per cent}.$$

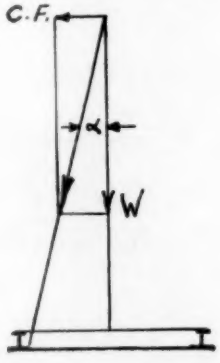
$$\text{Weight on Outer Rail} = \frac{90}{2}(1 - .214) = 35.4 \text{ tons},$$

$$\text{Weight on Inner Rail} = \frac{90}{2}(1 + .214) = 54.6 \text{ tons}.$$

Case No. 2: Lateral weight transfer, owing to centrifugal force, when no superelevation is provided on curves. This is similar to Case No. 1 except that the weight transfer will be from the inner rail to the outer rail. The same weight transfer factor obtains but, in this case, there is no superelevation and the value e must be secured in a different manner.

From Case No. 1, the weight transfer factor is $2he/G^2$, and $e = G \tan \alpha$.

Therefore, the weight transfer factor becomes $2h \tan \alpha/G$, where α is the angle between the component W and the



resultant of the components W and $C.F.$, as shown in the sketch, therefore,

$$\tan \alpha = \frac{C.F.}{W} = 0.067 \frac{V^2}{r},$$

$$\tan \alpha = 0.067 V^2 \times \frac{C}{5730} = .0000117 V^2 C,$$

and

$$R_0 = \frac{W}{2}\left(1 + 2\frac{h}{G} \times .0000117 V^2 C\right),$$

$$R_1 = \frac{W}{2}\left((1 - 2\frac{h}{G} \times .0000117 V^2 C\right).$$

For trains running at the same speed on the same curve, with no superelevation, the weight transfer factor is independent of the weight of the vehicle and it is directly proportional to the height of the centre of gravity above the top of the rail. In this particular case, consider a train speed of 100 m.p.h. on a one degree curve with no superelevation:

For 35-ton cars, $W = 35$; $h = 46.5$; $G = 56.5$; $V = 100$; $C = 1$,

$$2\frac{h}{G} \times .0000117 V^2 C = 2\frac{46.5}{56.5} \times .0000117 \times 100^2 \times 1$$

$$= 19.2 \text{ per cent.},$$

$$R_0 = \frac{35}{2}(1 + .192) = 20.9 \text{ tons},$$

$$R_1 = \frac{35}{2}(1 - .192) = 14.1 \text{ tons}.$$

For the 90-ton cars, $W = 90$; $h = 57$; $G = 56.5$; $V = 100$; $C = 1$,

$$2\frac{h}{G} \times .0000117 V^2 C = 23.8 \text{ per cent.},$$

$$R_0 = \frac{90}{2}(1 + .238) = 55.6 \text{ tons},$$

$$R_1 = \frac{90}{2}(1 - .238) = 34.4 \text{ tons.}$$

In both cases investigated, the shifting of the centre of gravity from the mid position of track gage has been neglected, even though it is realized that the centre of gravity will tend to shift toward the direction where the weight transfer is intensified. In other words, the centre of gravity of the vehicle is so displaced as to make the percentages of weight transfer indicated above actually greater than shown. It follows, therefore, that the calculated weight transfer is the minimum rather than a maximum figure. Furthermore, the weight transfer may be aggravated by the presence of low rail joints, track out of surface, etc., but low joints are particularly troublesome in cases of weight transfer and they appreciably increase the risk of a mishap under critical conditions.

An Electric Gas Generator.—IVAR HOLE, of Oslo, Norway, read a paper before the annual convention of the Canadian Gas Association recently, in which he described an apparatus that may be useful in cities with a surplus of cheap electricity, where the demand for gas for household or technical uses exceeds the capacity of the gas works. The apparatus, developed by a Norwegian firm, produces water gas from anthracite and steam. It consists principally of a vertically placed cylinder lined with firebrick and filled with carbonaceous material, which is charged at the upper end. Steam is introduced at the lower end and the gas taken out at the top. The electric energy is introduced near the bottom and at the top through carbon electrodes (Söderberg). Single phase current is used.

The first generator put into operation uses 250 Kw. and produces about 6000 cu. ft. per hour. The second has a continuous load of 400 Kw. and produces 10,000 cu. ft. per hour. Gas is composed principally of CO (48 per cent. vol.) and H_2 (51 per cent. vol.) and has a calorific value of 310 B.T.U. per cu. ft. It contains very little dust and is easily cleaned. The carbon material used in these generators is anthracite lumps not exceeding 4 inches, with an ash content of about 3 per cent. Eighteen pounds of anthracite are used per 1000 cu. ft. of dry gas, exclusive of a small loss in ash. Any low-ash coke of sufficient mechanical strength, also charcoal, is equally usable. The amount of steam required per 1000 cu. ft. of moist gas is 26 to 28 lbs.

R. H. O.

Bacterial Content of Kansas Dust Storm.—C. RITTER (*Safety Engineering*, Vol. LXIX, No. 6). A reprint of an article from *Public Health Reports*, May 3, is given which calls attention to the fact that dust storms which plagued large sections of the country recently not only were composed of dust but also were a carrier of germs. At the University of Kansas dust samples were collected on Petri dishes and it was calculated that 31,000 bacteria fell per square foot per minute. The colonies of bacteria appeared very similar to those formed by soil organisms, some of which will appear on plates made from raw waters. Of 11 colonies examined, all but 2 had formed spores in 24 hours. They were all rather large bacillus forms, and most of them were Gram positive. No coccus forms were found. This strongly indicated that the bacteria surviving in the dust were resistant soil types.

R. H. O.

SOME PIEZOELECTRIC AND ELASTIC PROPERTIES OF β-QUARTZ.

BY

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INTRODUCTION.

"High" or β-quartz is described by Sosman [1] as hexagonal trapezohedral or enantiomorphous hemihedral. He points out that crystals of this classification should exhibit piezoelectricity when subjected to shear stresses. This classification may also be described as hexagonal holoaxial.[2] β-quartz will be here shown to possess piezoelectric properties which are characteristic of hexagonal holoaxial crystals.

The piezoelectric [3] and elastic constants [4] are referred to a set of Cartesian axes in which the Z-axis coincides with the axis of hexagonal symmetry and the X-axis with an axis of digonal symmetry. Only rectangular crystal cuts with faces parallel to the coördinate planes are here considered. An X-face, for example, is one which is normal to the X-axis. When this face is a major surface, the plate is called an X-cut. The center of the rectangular parallelepiped is chosen as the origin so that the X, Y, and Z-faces are located respectively at $x = \pm x'$, $y = \pm y'$, and $z = \pm z'$.

If the components of strain and stress are expressed in the notation of Love,[5] the components P_x, P_y and P_z of polarization can be shown to be:

$$P_x = d_{14}Y_z; \qquad P_y = -d_{14}Z_x; \qquad P_z = 0; \tag{1}$$

$$P_x = e_{14}e_{yz}; \qquad P_y = -e_{14}e_{zx}; \tag{2}$$

in which e_{14} and d_{14} are respectively the piezoelectric constant

[1] Sosman, "The Properties of Silica," p. 568 (1927).
[2] Love, "Mathematical Theory of Elasticity," p. 155 (1920).
[3] Voigt, "Lehrbuch der Krystallphysik," p. 831 (1910).
[4] Ibid., p. 586.
[5] Love, "Mathematical Theory of Elasticity," pp. 38, 40, and 75 (1920).

and the modulus. It follows from (1) and (2) that no piezoelectric effect is associated with the components of tensile stress or strain. When an electric field of components E_x, E_y and E_z is applied, the components of strain and stress due to the converse effect are:

$$e_{xx} = e_{yy} = e_{zz} = e_{xy} = 0; \quad e_{yz} = d_{14}E_x; \quad e_{zx} = -d_{14}E_y; \tag{3}$$

$$X_x = Y_y = Z_z = X_y = 0; \quad Y_z = e_{14}E_x; \quad Z_x = -e_{14}E_y. \tag{4}$$

The components of strain and stress are also related by the equations:

$$\begin{aligned} e_{xx} &= s_{11}X_x + s_{12}Y_y + s_{13}Z_z, \\ e_{yy} &= s_{12}X_x + s_{11}Y_y + s_{13}Z_z, \\ e_{zz} &= s_{13}X_x + s_{13}Y_y + s_{33}Z_z, \\ e_{yz} &= s_{44}Y_z, \\ e_{zx} &= s_{44}Z_x, \\ e_{xy} &= 2(s_{11} - s_{12})X_y, \end{aligned} \tag{5}$$

$$\begin{aligned} X_x &= c_{11}e_{xx} + c_{12}e_{yy} + c_{13}e_{zz}, \\ Y_y &= c_{12}e_{xx} + c_{11}e_{yy} + c_{13}e_{zz}, \\ Z_z &= c_{13}e_{xx} + c_{13}e_{yy} + c_{33}e_{zz}, \\ Y_z &= c_{44}e_{yz}, \\ Z_x &= c_{44}e_{zx}, \\ X_y &= \frac{(c_{11} - c_{12})}{2} e_{xy}, \end{aligned} \tag{6}$$

in which c_{ij} and s_{ij} are respectively the elastic constants and moduli for this crystal class. Equations (5) and (6) show that the components of strain and stress which result from the application of an electric field do not directly involve (even in the case of resonance) any of the remaining components of strain or stress. In (5), for example, e_{xx} does not contain a term involving Y_z or Z_x. It follows that the only components of strain or stress which can be directly produced by the application of an electric field are e_{yz}, e_{zx}, Y_z and Z_x. Equations (3) and (4) further show that the components e_{yz} and e_{zx} are mutually independent in the sense that they depend respectively on E_x and E_y. Y_z and Z_x are likewise independent.

THE *yz* AND *zx*-SHEAR MODES.

Suppose that there exist in β-quartz mechanical modes of vibration whose displacements are described either by e_{yz} or e_{zx}. If an alternating electric field is applied along X, the group of modes described by e_{yz} will be driven into resonance at frequencies which agree closely with any natural frequency of vibration of these modes. Any mode which is described by e_{zx} is similarly excited by applying the field along Y. These two groups of modes, described by e_{yz} and e_{zx}, are denoted respectively as the *yz* and *zx*-shear modes. The natural frequencies of vibration of the *yz*-shear modes will be derived.

Let the high frequency electric field be applied along X. In view of (3), (4), (5) and (6) the differential equations of motion [6] reduce in the absence of body forces to:

$$\frac{\partial Y_z}{\partial z} = \rho \frac{\partial^2 v}{\partial t^2}; \qquad \frac{\partial Y_z}{\partial y} = \rho \frac{\partial^2 w}{\partial t^2}. \tag{7}$$

From (6), (7) and the definition of the components [7] of strain

$$\begin{aligned} c_{44}\left(\frac{\partial^2 v}{\partial z^2} + \frac{\partial^2 w}{\partial y \partial z}\right) &= \rho \frac{\partial^2 v}{\partial t^2}; \\ c_{44}\left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 v}{\partial y \partial z}\right) &= \rho \frac{\partial^2 w}{\partial t^2}. \end{aligned} \tag{8}$$

Suppose that prior to the instant $t = 0$ the crystal plate is subjected to a set of static stresses such that on its boundary all surface tractions except Y_z vanish. Let

$$Y_z = c_{44} e_{yz} = c_{44}\left[\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right] = M, \tag{9}$$

when $t = 0$, $y = \pm y'$, $z = \pm z'$ where M is a constant.

The equations

$$v = B \cos \beta y \sin \gamma z \cos \omega t; \qquad w = R \sin \beta y \cos \gamma z \cos \omega t \quad (10a);$$

or

$$v = B \sin \beta y \cos \gamma z \cos \omega t; \qquad w = R \cos \beta y \sin \gamma z \cos \omega t \quad (10b);$$

[6] Ibid., p. 83.
[7] Ibid., p. 38.

are solutions of (8) provided

$$c_{44}\frac{\gamma}{B}(B\gamma + R\beta) - \rho\omega^2 = 0;$$
$$c_{44}\frac{\beta}{R}(B\gamma + R\beta) - \rho\omega^2 = 0; \tag{11}$$

hence,

$$R = \frac{\beta}{\gamma}B. \tag{12}$$

The boundary condition (9) requires that

$$\omega^2 = 4\pi^2 f^2 = c_{44}/\rho(\beta^2 + \gamma^2) \tag{13}$$

in which $\beta = n\pi/2y'$, $n = 1, 2, 3$, etc.; and $\gamma = p\pi/2z'$, $p = 1, 2, 3$, etc. The frequency f_{np} which corresponds to a particular choice of n and p is:

$$f_{np} = \tfrac{1}{4}(c_{44}/\rho)^{1/2}(n^2/y'^2 + p^2/z'^2)^{1/2} \equiv \tfrac{1}{4}(c_{44}/\rho)^{1/2}G_{np}. \tag{14}$$

The choice of (10a or 10b) is not arbitrary but depends upon the integers n and p.

Similarly in the zx-shear mode

$$u = A\cos\alpha x \sin\gamma z \cos\omega t; \quad w = \frac{A\alpha}{\gamma}\sin\alpha x \cos\gamma z \cos\omega t; \tag{15a}$$

or

$$u = A\sin\alpha x \cos\gamma z \cos\omega t; \quad w = \frac{A\alpha}{\gamma}\cos\alpha x \sin\gamma z \cos\omega t; \tag{15b}$$

$$f_{mp} = (c_{44}/16\rho)^{1/2}(m^2/x'^2 + p^2/z'^2)^{1/2} \equiv \tfrac{1}{4}(c_{44}/\rho)^{1/2}G_{mp}. \tag{16}$$

The choice of $n = 0$ or $p = 0$ in (14) is consistent with only zero values of both v and w. This definitely excludes the possibility of shear (transverse) modes whose frequency is expressed by formulæ of the type[8, 9]

$$f = (q/4y')(c_{nn}/\rho)^{1/2}, \qquad q = 1, 2, 3, \text{ etc.} \tag{17}$$

Modes whose frequencies and displacements are in accord with those predicted by any approximate theory leading to (17)

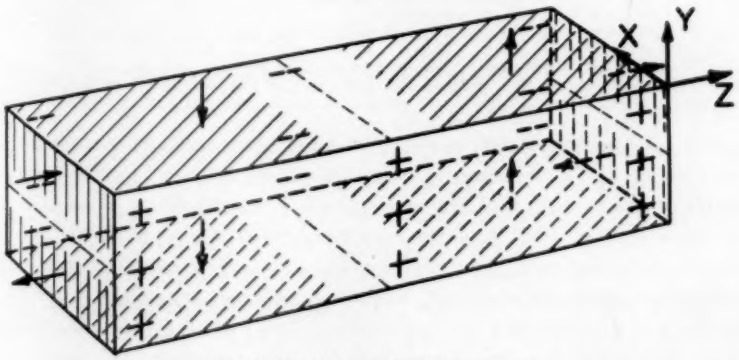
[8] I. Koga, *Physics*, **3**, 70 (1932).
[9] Lack, Willard and Fair, *Bell Sys. Tech. Jour.*, **13**, 453 (1934).

have not been found by the writers in either α [10] or β-quartz with the aid of interferometer methods.

The simplicity of equations (5) and (6) as compared to the corresponding equations in α-quartz (see equations (7) and (25) in a paper by W. P. Mason) [11] render the numerous assumptions which follow Mason's equation (28) unnecessary in the case of β-quartz. In α-quartz the strain component e_{yz} is involved with the components e_{zz} and e_{yy}; and the component e_{zx}, with e_{xy}. This statement is also confirmed by the interference patterns formed by a large variety of vibrating plates of α-quartz. Both theory and experiment show that the *yz* and *zx*-shear modes do not appear independently and that the considerations leading to (14) or (16) are inadequate as explanation of the elastic behavior of plates of α-quartz of the usual orientation. In β-quartz, on the contrary, the interference patterns have shown conclusively that the *yz* and the *zx*-shear modes do occur independently and that the considerations leading to (14) or (16) are adequate as explanation of the elastic behavior except when the shear modes are mechanically coupled with other modes of vibration.

In Fig. 1 the antinodes of displacements executed in a

FIG. 1.



The first mode, f_{11}, of the *yz*-shear group.

direction normal to the surfaces are marked by the shaded areas for the first (and simplest) mode, f_{11}, of the *yz*-shear

[10] Article submitted for publication in *Physics*.

[11] W. P. Mason, *Bell Sys. Tech. Jour.*, **13**, 434 and 447 (1934).

group. The X-faces become oppositely and uniformly charged. In any mode f_{np} there are $n + 1$ and $p + 1$ antinodes upon the Z and Y-faces, respectively. When either n or p, or both, are even, the sum of the charges upon either X-face is zero. As a consequence, only those modes for which both n and p are odd can be easily excited when full electrodes are used. This conclusion was verified experimentally in β-quartz. The relative motions indicated by the arrows are those predicted by (10a and 10b). In the modes f_{1p}, $p > 1$, the motion of the Y and Z-faces are strikingly similar to those produced by the propagation along Z of the standing flexural wave trains in which v and w are the major displacements. This situation favors the mechanical coupling of the flexural and the yz or zx-shear modes.

OBSERVATIONS.

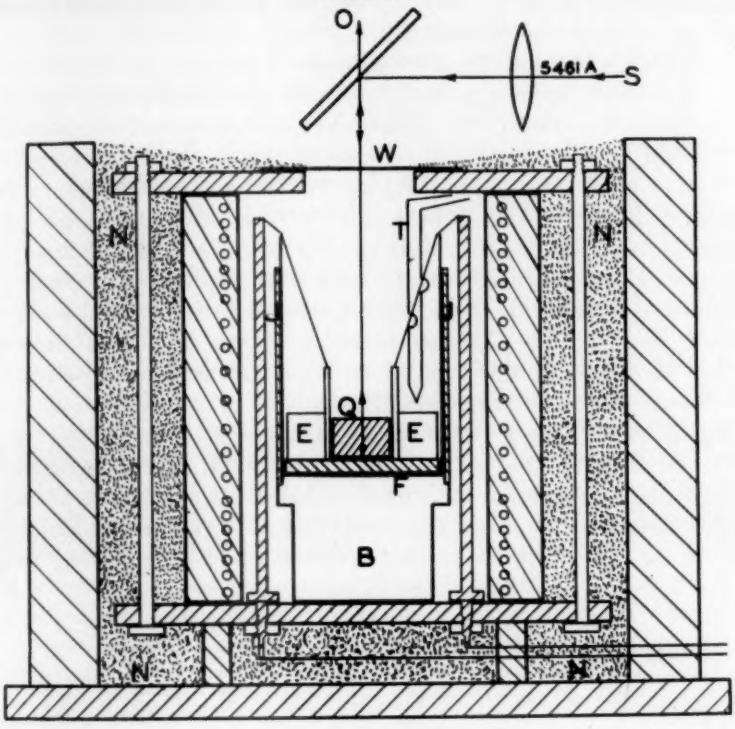
The crystals of Table I were heated in an electric furnace which was designed to surround the crystals with an environment of uniform temperature. The temperatures were estimated to 1° C. by means of a chromel-alumel thermocouple calibrated at the melting points of Zn and Sn. The nickel electrodes EE, Fig. 2, were connected through platinum leads either directly or inductively with a Hartley oscillator whose frequency was determined with a precision wavemeter. The motion of any surface of the crystal Q was studied by observing from O, through a mica window W, the thin-film interference fringes formed between this surface and an optical flat F of fused quartz. The copper jacket J, which served to equalize the temperature, was lined with mica to prevent accidental short-circuiting of the electrodes. Another sheet of mica separated the electrodes from the polished surface of the fused quartz flat.

TABLE I.

Dimensions of the Crystal Plates.

Crystal.	Cut.	$2x'$ mm.	$2y'$ mm.	$2z'$ mm.
1....	X	5.857	6.246	9.264
2....	X	5.877	11.295	17.719
3....	Y	10.186	7.116	15.791
3a...	Y	10.150	7.116	15.753

FIG. 2.



Furnace Arrangement. *Q*, quartz plate; *F*, fused quartz optical flat; *EE*, nickel electrodes; *T*, thermocouple; *J*, copper jacket; *W*, mica window; *S*, source of light; *O*, observer; *B*, iron block; *N*, infusorial earth.

The temperature of transition from α to β-quartz was found to lie in the narrow range 573.5° to 575° C. Crystals 1, 2, 3 and 3a oscillated violently in the *yz* or *zx*-shear modes at temperatures ranging from 575° to 847° C. There was no direct evidence that piezoelectricity in quartz above 575° C. is due to a remnant of α-quartz. On the contrary β-quartz proved, in many ways, to be a superior piezoelectric material to α-quartz. It was an easy matter, particularly in the case of f_{13} of either shear mode, to stabilize a regenerative Pierce or Miller [12] oscillator or even the Hartley oscillator.

Crystal 1 was examined for the *zx*-shear mode. With the electric field applied along *Y*, f_{13} was positively identified at a

[12] A. Crossley, *P. I. R. E.*, 15, 9, 1927.

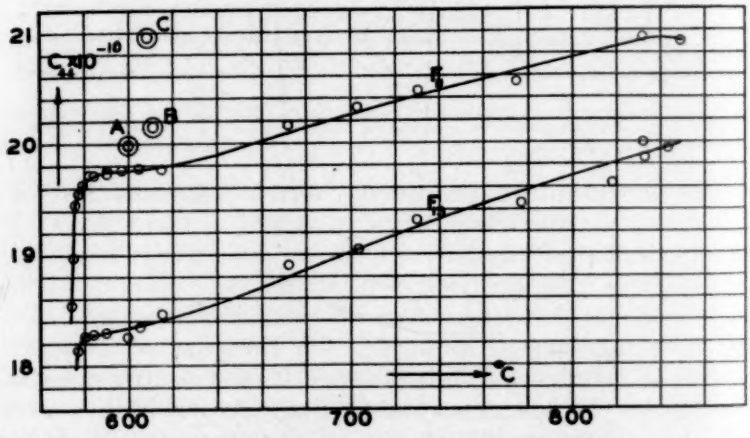
frequency of 514.2 kc./sec. at 655° C. The plate was broken before f_{11} could be identified.

Crystals 2, 3 and 3a were examined for the yz-shear mode. With the field applied along X, f_{13} was identified in crystal 2 at 264.5 kc./sec. at 656° C. This crystal, too, was broken before f_{11} could be identified.

In crystal 3, f_{11}, f_{13} and f_{33} were positively identified. The motion of the Y and Z-faces in the case of f_{11} was approximately that described in Fig. 1. The motion of these faces in f_{13} and f_{33} agreed quite closely with that predicted but showed definite effects of mechanical coupling of the shear mode with other modes. In f_{11}, the yz-shear mode remained loosely coupled or uncoupled throughout the entire temperature range of β-quartz. Similar comments apply to crystal 3a, which was formed by polishing every face of crystal 3.

The elastic constant c_{44} can be deduced at any particular temperature from the measured value of f_{np} by means of (14) when the density ρ and G_{np} are known. The dependence of c_{44} upon the temperature is plotted in Fig. 3 from data

FIG. 3.



c_{44} in dynes/cm.^{2} as a function of temperature. A, B and C are respectively the values of c_{44} from f_{11} of crystal 3a, f_{13} of crystal 2, and f_{13} of crystal 1. The curves were obtained from crystal 3.

secured from crystals 1, 2, 3 and 3a. In computing c_{44}, it was assumed that the density ρ and the crystal dimensions were those measured at room temperature ($\rho = 2.654$ grs./cm.^{3}) c_{44}

falls rapidly near the temperature of transition from β to α-quartz. At the transition point the amplitude of vibration of the mode f_{11} decreased or increased rapidly according as one lowered or raised the temperature. The temperature of transition was very sharp. Below the transition point the presence of the yz-shear mode in any of the many vibrational patterns was not recognized. These vibrational patterns were studied at room temperature in crystal 3a for the presence of f_{11}, f_{31}, f_{13} and f_{33} of the yz, zx, and xy shear groups, using as approximate guides the numerical values of their frequencies computed from the known values of c_{44} and $(c_{11} - c_{12})/2$ in α-quartz. As in the case of many other crystals which have been studied at room temperature, conclusive evidence for the presence of these shear modes was not obtained. Some of the vibrational patterns appeared to contain both the xy and zx-shear modes, giving support to the conclusion that these modes are bound together in α-quartz. The difference in the behavior of α and β-quartz as regards to the yz and zx-shear modes was striking. Further, since longitudinal modes of vibration did not appear in these crystals of β-quartz, the elastic and piezoelectric behavior of β-quartz is of the type predicted. These results confirm but do not prove the statement that β-quartz is hexagonal holoaxial since enantiomorphous hemihedral crystals of the tetragonal system [13] should show similar piezoelectric and elastic properties. That β-quartz belongs to the hexagonal system, is well established by the X-ray data of Wyckoff,[14] Bragg and Gibbs.[15, 16]

In estimating the best value of c_{44} in β-quartz from these measurements, one is justified in considering only those measured from f_{11} since f_{13} and f_{33} are mechanically coupled. At 600° C. the value of c_{44} from crystal 3 is 19.76×10^{10} dynes/cm.^{2} while that from crystal 3a is 19.98×10^{10}. The average value 19.87×10^{10} dynes/cm.^{2} approximates the true value within the limitations imposed by the simplicity of the theory leading to (14) and by the choice for ρ and the crystal dimensions the values measured at room temperature.

[13] Voigt, "Lehrbuch der Krystallphysik," pp. 586 and 830 (1910).
[14] Wyckoff, *Zeitschr. f. Krystallographie*, **63**, 507 (1926).
[15] Bragg, *Jour. Soc. Glass Tech.*, **9**, 272 (1925).
[16] Bragg and Gibbs, *Proc. Roy. Soc.*, **109**, 405 (1925).

Several unsuccessful attempts have been made by the writers to quench β-quartz with the hope of securing a specimen of it at room temperature. If stable specimens of this material could be secured, they would be of great value for such purposes as the stabilization of radio broadcast frequencies.

γ-QUARTZ.

As the temperature of crystal 3 was raised or lowered in the neighborhood of 850° C., the modes f_{11} and f_{13} of the yz-shear group ceased to vibrate at some temperature between 844° and 851° C. 847° C. was, accordingly, concluded to be the temperature of transition from β to γ-quartz. It is not certain whether γ-quartz is a new state of quartz or whether it is tridymite,[17] which has been found to be stable above 870° C. The transition temperature was sharp and the disappearance or reappearance of γ-quartz was rapid whereas the transition to and from tridymite is said to be sluggish.[17] An amplifier was connected across a portion of the plate circuit so as to produce a click whenever the crystal plate started to oscillate. No vibrations of any kind were detected in the range 850° to 925° C. either by listening for these clicks or by watching the interference pattern formed as, previously explained, from one of the surfaces of the crystal. It appears, therefore, that neither γ-quartz nor tridymite is piezoelectric. They belong either to class (21) or to class (24).[18]

CONCLUSION.

1. It is shown by an indirect method that β-quartz is piezoelectric. The conclusion reached by Perrier [19] is not entirely correct.

2. The piezoelectric and elastic properties of β-quartz are those which are theoretically characteristic of the hexagonal holoaxial class.

3. A simple theory of the so-called yz and zx-shear modes is verified. These modes are shown, both by theory and experiment, to exist independently in β-quartz but not in

[17] Winchell, "Microscopic Character of Artificial Minerals," pp. 192–3.
[18] Voigt, "Lehrbuch der Krystallphysik," p. 831.
[19] Perrier, *Arch. Sci. et Phys. Nat.* (4), **41**, 493 (1916).

α-quartz. This conclusion, as it applies to α-quartz, is not in full accord with that drawn by Mason.[20]

4. There exists at 847° C. a transition point from β to some other form of quartz which is tentatively called γ-quartz since it may prove to be tridymite. Neither γ-quartz nor tridymite appear to be piezoelectric.

5. Using the values of ρ and of the crystal dimensions measured at room temperature, the best measured value of the elastic constant c_{44} in β-quartz at 600° C. is 19.87×10^{10} dynes/cm.^{2} When the actual values of ρ and the crystal dimensions at 600° C. are computed from the values at room temperature with the aid of the X-ray data of A. H. Jay,[21] the corresponding measured value of c_{44} is 19.36×10^{10} dynes/cm.^{2}

6. β-quartz would be a valuable piezoelectric substance if it could be rendered stable at room temperature.

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[20] Mason, *Bell Sys. Tech. Jour.*, **13**, 431 (1934).

[21] A. H. Jay, *Proc. Roy. Soc.* A, **142**, 237 (1933).

Rotating Foundation Caissons Drill Their Way to Rock.—An interesting account of how huge steel cylinders with a sawtooth cutting edge are being drilled down to rock through 65 to 70 ft. of sand, clay and boulders, is given in *Engineering News Record*, Vol. 115, No. 2.

The occasion is the new Federal Building in New York City, and the cylinders, 4 to 8½ ft. in diameter and averaging 66 ft. in length, are to form the foundation caissons. They are spun through virgin soil, while high pressure revolving jets excavate most of the contents of the shell during the sinking operation. The sinking progress varies with soil and boulder conditions but usually runs between 12 and 20 ft. per hour. Thus caissons are being sunk in four to six hours, as compared with the usual six to eight days required under compressed air methods.

Fabrication of each caisson is in two cylindrical sections approximately equal in length, by shop welding. The cutting teeth are formed on the lower end with a gas torch. As they are cut, alternate teeth are bent inward and outward to give a set as in a saw; the amount of set is such as to produce a kerf twice the thickness of the cutting edge plate. To prevent wear, their exposed surfaces are coated with a thin layer of tungsten carbide, applied by gas welding.

The rig for sinking the caisson resembles a huge skid piledriver, the tower 78 ft. high. The rotating head assembly weighs 11 tons and contains a 125 hp. electric motor that drives the rotor head through a worm-gear reducer, gearing the motor down 220 to 1 and making a torque of 1,000,000 ft.-lb. available for rotating the cylinders. Connected to the driving shaft is the rotor head, equipped with driving lugs to engage lugs welded to the cylinder head plate.

R. H. O.

CONSERVATION OF DIRECTION IN THE IMPACT OF HIGH ENERGY PARTICLES.

BY

W. F. G. SWANN, D.Sc.,

Director of the Bartol Research Foundation of The Franklin Institute.

BARTOL RESEARCH FOUNDATION
Communication No. 89.

Suppose a photon or high energy particle collides with a stationary particle, and as a result both are found in motion; or, suppose that as a result several other particles are ejected from the originally stationary particle, or even that they are *created*. It is the purpose of this note to show that if all the material particles have energy so large that their rest masses are negligible compared with their actual mass, and if no potential energy considerations are involved, then conservation of energy and momentum requires that all the particles will travel very accurately in the direction of the original photon or high energy particle. The conclusion is of importance in impacts concerned in cosmic ray phenomena. It is probably known to many mathematical physicists; nevertheless, the writer's experience on citing it has led him to conclude that it is not as widely realized as might be supposed, and that the completeness of perpetuation of direction is seldom realized. The energy E and the momentum M of a photon are given by

$$E = h\nu; \qquad M = h\nu/c. \tag{1}$$

The corresponding quantities for a material particle are

$$E = (m - m_0)c^2; \qquad M = mu, \tag{2}$$

where m is the mass, m_0 the rest mass and u the velocity. For all such energies as are concerned in cosmic ray phenomena, u in (2) may be put equal to c; although, of course, such a change must not be made in the u implicitly contained in m through the relation $m = m_0(1 - u^2/c^2)^{-1/2}$. For sufficiently

high energies, (2) thus become

$$E = mc^2; \qquad M = mc. \tag{3}$$

Thus, for sufficiently high energies, we have for both photons and electrons,

$$M = E/c, \tag{3}$$

the direction of M being of course that of the velocity.

Suppose that the particle which is in motion before the impact is denoted by subscript unity, and that the other particles which figure in the problem after impact are denoted by subscripts 2, 3, etc. and let dashed letters refer to the conditions after impact. Then conservation of energy requires

$$E_1 = E_1' + E_2' + E_3' + \text{etc.} \tag{4}$$

If θ refers to the angle made by the direction of a particle's motion with the initial direction of motion of the particle denoted by subscript unity, the conservation of momentum requires that

$$E_1/c = (E_1' \cos \theta_1)/c + (E_2' \cos \theta_2)/c + \text{etc.} \tag{5}$$

The corresponding equations for the other directions will not be required. Now since $\cos \theta$ is always less than or equal to unity, the only possible way in which (4) and (5) can be simultaneously satisfied is by

$$\cos \theta_1 = \cos \theta_2 = \cos \theta_3 = \text{etc.} = 1, \tag{6}$$

which proves the proposition.

An element of interest now arises by considering how far the conclusion reached in (1) may be departed from in practice. Equation (4) holds always. If however the rest mass of any of the particles is not negligible, each term of (5) should be multiplied by a factor $mu/(m - m_0)c$, with appropriate subscript or dash to correspond to the particle concerned, unless the particle is a photon, in which case the factor is absent. Thus (5) becomes modified to

$$\frac{u_1}{c(1 - m_1/m_{10})} E_1 = \frac{u_1'}{c(1 - m_1'/m_{10})} E_1' \cos \theta_1 + \frac{u_2'}{c(1 - m_2'/m_{20})} E_2' \cos \theta_2 + \cdots. \tag{7}$$

If any of the particles are photons, the corresponding factors involving u and m are absent.

Now suppose as an example we consider a case where the material particles are of the electron type. Then, even if the lowest energy concerned is as low as 10^8 electron volts, we have for such a particle

$$u/c(1 - m/m_0) < 1.005.$$

Hence (7) assumes the form

$$(1 + \epsilon_1)E_1' = (1 + \epsilon_1')E_1' \cos\theta_1 + (1 + \epsilon_2')E_2' \cos\theta_2 + \cdots, \quad (8)$$

where all of the ϵ's are less than 0.005. Combining (4) and (8), it is of course *possible*, in the case of a large number of particles, to permit say $\cos\theta_n$ to be appreciably different from unity, while all the other values of the $\cos\theta$'s are sensibly unity, and the ϵ's associated with them make up the deficit resulting from $\cos\theta_n$. While such an adjustment is incapable of being denied without appeal to the more fine grained theory structure than is contained in conservation of energy and momentum, it is obviously fantastic; and, in any case would be inapplicable where only a few particles were concerned. The common sense view is to the effect that no $\cos\theta$ can fall below unity to a greater extent than the largest ϵ exceeds unity. In other words, we should expect that, in the example cited, $\cos\theta_n > 1 - 0.005$, which gives $\theta < 0.1$ i.e. less than six degrees. For a case where the minimum energy is 10^9 electron volts, the corresponding result would be less than 0.2 degree. When heavier particles are involved the requirements necessitating perpetuation of direction are less stringent. In fact, the permissible angles of deflection are proportional, as an approximation, to the square root of the rest mass for a given energy which, in the case of a proton, for example, would cause the foregoing example to be incapable of denying deflections of large amounts. The energy equivalent of the rest mass of a proton is in fact about 10^9 volts.

The foregoing matters have important bearing upon the perpetuation of direction of primary cosmic rays by secondaries produced by them. They also have significant bearing

upon perpetuation of direction in the case of generation of positrons and electrons from photons and therefore upon that theory of stoss (atomic burst) production which depends upon such creation of material particles. For, except where heavier particles, or potential energy considerations are involved, it is difficult to see how such theories could prevent any appreciable spreading of the shower particles.

ANALYSIS OF COSMIC RAY DEFLECTION EXPERIMENTS. II.

BY

W. E. DANFORTH, JR.

BARTOL RESEARCH FOUNDATION

Communication No. 90.

The method of analyzing the results of cosmic ray deflection experiments, developed in a previous paper, is here extended to the case where the region of uniform deflecting field is of the same width as that of the counters. In this form it is applicable to the electrostatic deflection experiment of Lenz, and to the electrostatic and magnetic experiments of W. F. G. Swann and the writer. The magnetic experiments of Curtiss and of Mott-Smith are reëxamined in the light of the energy distribution recently published by Anderson and Neddermeyer. The latter's result is found to be not inconsistent with the assumption that the induction B gives the correct force; the result of the former requires the addition of low energy rays to the distribution.

1. In a previous issue [1] the writer developed a geometrical analysis for interpreting experiments in which the magnetic deflection of cosmic ray electrons is detected by means of Geiger-Mueller counters. It was applied to that type of experiment in which three or more counters are arranged in vertical line with a region of uniform magnetic field between two of them.

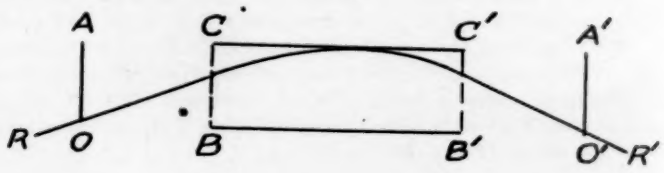
One observes, with this arrangement, a diminution of counting rate when the field is applied. The problem is to calculate, for a given distribution-in-energy of the cosmic ray electrons, the fractional diminution which a given strength of field would produce.

The previous analysis was developed only for the case where the lateral extent of the field region was considerably greater than the counter width. In the electrostatic experiments which have been performed, however, and also in a magnetic experiment recently carried out by Dr. W. F. G. Swann and the writer, the field region was of sensibly the same width as the counters. The writer has carried out this somewhat more cumbersome computation, and, since applications of it have appeared on two occasions, it seems desirable to make the details of the method employed publicly accessible.

The recently published results of Anderson and Neddermeyer,[2] on the cosmic ray energy distribution as observed in the Wilson cloud expansion chamber, permit more intelligent discussion of deflection experiments than has heretofore been possible. The writer will, therefore, reëxamine the results of Curtiss [3] and of Mott-Smith [4] in the light of this new data.

For a general discussion of the geometrical problem the reader may refer to the first paper.[1] The arrangement with which we are at present concerned is shown schematically in Fig. 1. The lines OA and $O'A'$ represent diameters of cylin-

FIG. 1.

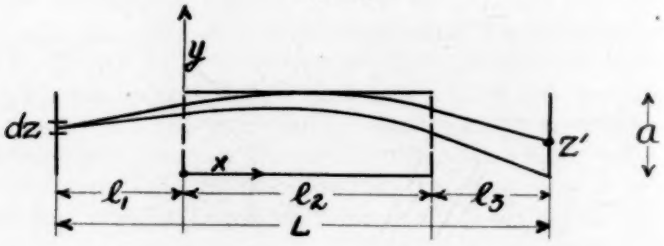


drical counters having their axes normal to the paper. The uniform deflecting field is confined to the rectangle $BCC'B'$. If electric, its direction is parallel to OA; if magnetic, normal to the paper.

The path of the lowest energy ray which can pass through both counters with the field *on* is shown by RR'. It passes through corresponding edges of both counters; is tangent to the opposite boundary of the field region.

Letting a represent the width (OA) of the counters, and S, their length (normal to the diagram), the element Sdz of the first counter (see Fig. 2) contributes, in the absence of any deflecting field, jS^2adz/L^2 counts per second, where j is the

FIG. 2.



particle intensity. Application of the field reduces the available area of the second counter from aS (its value without the field) to $z'S$, where z' is the final ordinate of the tangent ray shown in Fig. 2. The counting rate due to dz is therefore reduced to $jS^2z'dz/L^2$, which, when integrated over all dz's, gives, for a given energy, the counting rate in the presence of the field. In assigning the limits for this integration one must take care that only those values of z are used for which the corresponding z' lies within the boundaries of the last counter. All dz's for which z' is greater than a contribute, of course, as much as without the field, while those for which z' is less than zero contribute nothing. The whole situation is taken account of by the following equation (1), of which a more detailed discussion may be found in the preceding paper.[1] For a given energy the fraction (p) permitted by the field may be written:

$$p = \frac{1}{a^2}\left\{az_0 + \int_{z_0}^{z_1} z'dz\right\}, \tag{1}$$

where z_0 is the value of z for which z' is equal to a, and z_1 the value for which z' is equal to zero. In carrying out the calculation one must observe the following rule. When z_0 is less than zero, use the value $z_0 = 0$; when z_1 is greater than a, use the value $z_1 = a$.

The way in which the present analysis differs from that of the preceding paper is in the formulation of z' as a function of z. We are at present considering two cases: (a) An electrostatic field in air, the electrons suffering no loss of energy, (b) A magnetic field in iron, the electrons losing v equivalent volts per cm. of path. I shall first outline a general method which later will be applied to both cases.

It will be shown in later sections that the path in the region of uniform field conforms, in both cases, to a differential equation of the type

$$\frac{d^2y}{dx^2} = Y_1(V, x), \tag{2}$$

where y and x are coördinates as indicated in Fig. 2, and V is the energy of the particle. The field strength and energy loss

per cm. of path are of course also present in the right hand side but need not be explicitly represented.

Integrating this twice with respect to x gives us the equation

$$y = Y(V, x, m, y_0),$$

where m and y_0 are arbitrary constants, corresponding respectively to the slope and ordinate of the path at the beginning of the field region. By noting that $y_0 = z + ml_1$ this equation may be written

$$y = Y(V, x, m, z). \tag{3}$$

The value of the parameter m is now defined by imposing the condition that the path be tangent to the boundary of the field region. One equates the derivative of (3) to zero and solves for x_{max}. The resulting expression for x_{max} is then substituted in (3), setting y equal to a, which gives one the equation,

$$M(m, z, V) = 0. \tag{4}$$

If (4) can be solved conveniently for m, the result may be algebraically substituted in (3). When energy loss has to be considered however, (4) must be solved graphically for values of m corresponding to all values of z and V. In either case, however, one has, in effect,

$$y = Y(V, x, z) \tag{5}$$

as the equation of the limiting tangent ray. The value of the final ordinate z' of the tangent ray may now be computed from (5) by means of the relation.

$$z' = Y(V, l_2, z) + l_3\left[\frac{d}{dx} Y(V, x, z)\right]_{x=l_2} \tag{6}$$

and then either z' or z may be computed in terms of the other. Substitution (6) in (1) will therefore give one the fraction (p) permitted by the field of all rays of a given value of energy. In actual application one will probably prefer to have the fraction eliminated (ϵ) which is of course equal to $1 - p$.

In a given experiment one measures a fractional diminution (E) when the field is applied. If $f(V)dV$ represents the

probability that a ray, which has been recorded without the field, has energy between V and $V + dV$, the observed diminution will be given by the equation

$$E = \int_0^\infty \epsilon f(V) dV. \tag{7}$$

The function $f(V)$ is dependent upon the amount of absorbing material present in the apparatus. If V_0 is the minimum energy which a ray must have in order to record, $f(V)$ is zero for all energies less than V_0.

2. The above method will now be applied to those experiments in which the rays are deflected by an electrostatic field between the plates of a "condenser." The differential equation to be used is derived from the relativistic equation

$$\frac{d}{dt}\left(m\frac{dy}{dt}\right) = -eX$$

where m is the relativistic mass, X the field strength, and e the electronic charge. Assuming that the slope dy/dx of the path is everywhere small compared to unity, one has

$$\frac{d^2y}{dx^2} = -\frac{X}{V}\frac{1 + eV/m_0c^2}{2 + eV/m_0c^2}, \tag{8}$$

where m_0 is the rest mass, and V the energy of the particle in terms of corresponding potential difference in electrostatic units. For large energies (10^7 volts or more) the right hand side is sensibly $-X/V$. The simplicity of this equation enables one to carry out the method of section 1 algebraically. Performing the indicated integrations and substitutions one gets

$$z' = z - kA + L\sqrt{k^2l_1^2 + 2k(a - z)}, \tag{9}$$

$$z_0 = a - k(L^2 - A - Ll_3), \tag{10}$$

$$z_1 = k(A - L^2) + L\sqrt{k^2l_3^2 + 2ka}, \tag{11}$$

$$\int_{z_0}^{z_1} z'dz = \frac{1}{2}[z_1^2 - z_0^2] - kA[z_1 - z_0] - \frac{LB^{3/2}}{3k}[(1 - qz_1)^{3/2} - (1 - qz_0)^{3/2}], \tag{12}$$

where
$$A = \frac{l_2^2}{2} + l_2 l_3 + L l_1,$$
$$B = k^2 l_1^2 + 2ka,$$
$$q = 2k/B,$$
$$k = X/V.$$

To obtain the numerical results, z_0 and z_1 must be computed for values of energy in the desired range and the results made to conform to the rule * stated just below equation (1). Then the integral (12) and finally the values of p (and ϵ) may be calculated.

The minimum energy which a ray can have and still record on both counters is computed by setting z_1 equal to zero and solving for V. This results in the formula

$$V_1 = X \frac{A^2 - L^2 l_1^2}{2L^2 a}, \tag{13}$$

which gives the energy corresponding to the ray RR' in Fig. 1.

3. In treating the problem of magnetic deflection in iron one again makes use of the fact that the angle between the path and the x-axis is small. One starts with the equation

$$\frac{d}{dt}\left(m \frac{dy}{dt} \right) = - He\sigma,$$

where σ is the velocity of the particle at the point under consideration, with e and H now in electromagnetic units. Expressing kinetic energy and velocity in terms of equivalent potential difference (in e.m.u.), and neglecting the first derivative term, this may be written

$$\frac{d^2y}{dx^2} = - \frac{Hc}{V'} \cdot \frac{1}{\sqrt{1 + 2m_0c^2/eV'}},$$

where V' represents energy at a point. Now introducing an energy loss per cm. (v) and assuming that it is independent of

* The fact that z_1 has a maximum when considered as a function of energy necessitates an amplification of the rule. As the energy increases and z_1 becomes greater than a, one should use the value $z_1 = a$ for *all* higher values of energy, even though the calculated z_1 actually decreases and again becomes less than a. The decreasing limb of the curve corresponds to rays having points of tangency outside of the field region, and has no physical significance.

energy, we have, for high energies

$$\frac{d^2y}{dx^2} = -\frac{Hc}{V - vx}, \tag{14}$$

where V is now the initial energy of the particle. Using equation (14) as the starting point for the analysis outlined in section 1, one has, corresponding to equation (3)

$$y = -\frac{HcV}{v^2}\left\{ \alpha x + (1 - \alpha x)\log(1 - \alpha x) \right\} + m(l_1 + x) + z, \tag{15}$$

where $\alpha = v/V$ and, corresponding to (4)

$$\frac{m}{v} - \frac{Hc}{v^2}\left(1 - e^{-mv/Hc}\right) = \frac{1}{V}\Big[(a - z) - ml_1 \Big], \tag{16}$$

which is to be solved graphically for m.

The final result, as expressed in equation (1), involves an integration of z' with respect to z. In the present case this must be done graphically. Therefore, for any given value of energy V we must have values of z' corresponding to a number of values of z between 0 and a. In order to do this one must first have a number of values of m corresponding to values of z between 0 and a.

To obtain solutions of (16) one plots the left hand side, which is independent of z and V, as a function of m. The right hand side is a double family of straight lines in m whose parameters are z and V. For every value of V concerned, one computes the intercepts for the appropriate values of z. Then, laying down a straight edge on a pair of intercepts, the corresponding value of m is given by the abscissa of the point of intersection with the curve representing the left hand side.

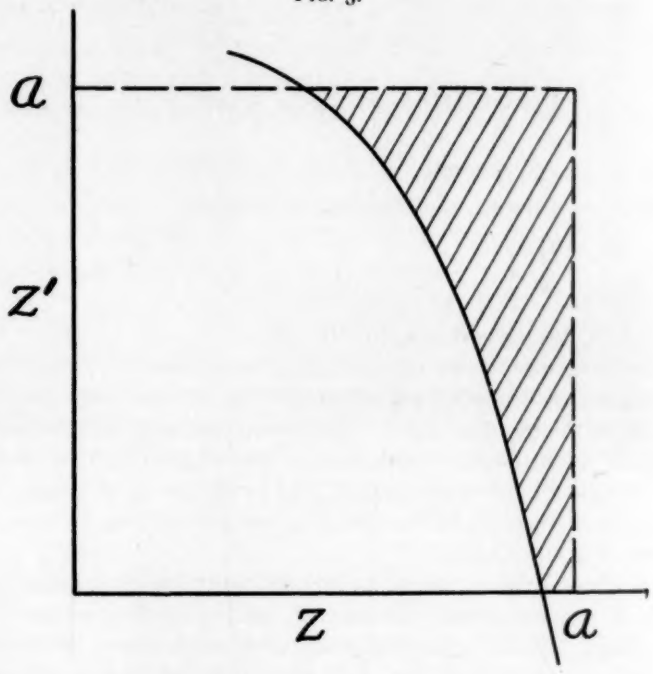
Values of z', the final ordinate of the tangent ray, are computed from the following expression, which is obtained by substituting (15) in (6).

$$z' = z + mL - \frac{Hc}{v}\Big[l_2 - \Big(l_2 + l_3 - \frac{V}{v}\Big)\log\Big(1 - \frac{vl_2}{V}\Big)\Big]. \tag{17}$$

If one now substitutes in this equation (17) the graphically

determined m-values, one gets values of z' which enable one to carry out, by means of a planimeter, the integration indicated in equation (1). Plotting z' as a function of z will give a diagram similar to Fig. 3. The unshaded fraction of the

FIG. 3.



square gives the value of p. One can see that by saying this one says exactly what equation (1) with its attendant rule says. The fraction eliminated ϵ is therefore given by the shaded fraction of the square.

The presence of one or more counters between the two extreme ones affects the result in no way, as long as they are of the same width as the extreme counters, and in line with them.

4. The results of section 2 have been applied to an experiment by W. F. G. Swann and the writer,[5] and to an experiment by Lenz,[6] and a discussion, on this basis, of the comparative results has appeared elsewhere.[5]

In a previous paper [1] the writer has discussed the experiments of Curtiss and of Mott-Smith relative to the question of magnetic fieldstrength within magnetized iron. Dr. Swann and the writer have recently completed another experiment on the deflection within magnetized iron, and the results, analyzed according to the method of section 3, are in process of publication. Uncertainties in the energy distribution and in values of energy loss prohibit an exact determination of the effective fieldstrength. Taking the various sources of error into account, however, it appears that our results are consistent with a fieldstrength of value somewhere between the measured induction B and $B/3$. It is certainly not the quantity usually represented by H. We are including in the paper a theoretical discussion as to the possibility of the effective force being different from B.

The new energy distribution data has been applied to Mott-Smith's experiment using the analysis of the preceding paper.[1] He observed a diminution of 6 per cent. with a standard deviation of 5 per cent. I calculate that if the energy loss v is 30×10^6 volts/cm. Mott-Smith's effect should have been $11\% \pm 2\%$ while if v is equal to 60×10^6 his effect would be $6\% \pm 1\%$. The tolerances in these computed percentages are lower limits to standard deviations corresponding to statistical fluctuations in Anderson's data. This bears out the conclusion of the preceding paper to the effect that Mott-Smith's result is not incompatible with the assumption that the vector B gives the correct force.

The distribution data does not extend to sufficiently low energies for a satisfactory comparison to be made with the result of Curtiss. For the cut-off curve of Curtiss's experiment the reader may refer to the preceding paper.[1] The writer has made the assumption, however, that the data is correct for all energies above 3×10^8 volts and has calculated the number of rays below 3×10^8 which must be added to account for Curtiss's 33 per cent. diminution. The latter's experiment eliminated all energies below 1.5×10^8 and, with the field off, included all energies down to 2 or 3×10^7. The number of rays to be added depends on how this number is distributed in energy. A lower limit is obtained by assuming that all the added rays are below 1.5×10^8, and for a reason-

able upper limit one can assume that they all lie between 1.5 and 3×10^8. Doing this one obtains the values: Lower limit, 41 rays; upper limit, 71 rays. The distribution to which these rays are added contains 96 rays altogether.

Pertinent to this matter is the result of Street, Woodward, and Stevenson [7] who found that 30 low energy rays had to be added to the distribution data to bring their absorption measurements into agreement with Anderson's energy loss determination. Such calculations as this, and as the one the writer has just described, are subject to considerable uncertainty depending upon the manner in which the low energy part of the distribution data is handled. The writer used a frequency polygon based on the published energy values. If he had used a monotonically decreasing smooth curve he would have needed to add fewer low energy rays.

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NOTES FROM THE U. S. BUREAU OF STANDARDS.*

ULTRAVIOLET SOLAR RADIATION INTENSITIES.

RP816 in the August number of the *Journal of Research* describes the making of ultraviolet filter transmission measurements, using a newly devised portable precision ultraviolet meter (*J. Research NBS*, **12**, 231 (February, 1934), RP647) and four glass filters, giving the spectral quality and total intensity in the band of ultraviolet solar radiation extending from about 2,900A to 3,500A. At the high altitude station (Flagstaff, Arizona) data were obtained on solar ultraviolet intensities under various conditions; high and low humidity, large and small air masses, clear and smoky skies. The data obtained at sea level stations (Washington, D. C., and San Juan, P. R.) are of interest in connection with the question of ultraviolet intensities in the tropics, as compared with similar stations at higher latitudes.

Data are given on the amount of ultraviolet transmitted through light fog, and on the amount reflected by the sky and by snow; also the effect of altitude and latitude on the solar ultraviolet intensity at the earth's surface.

The observations show that, while a light fog greatly reduces the intensity (when the sun appeared as a distinctly outlined white disk, the intensity was reduced to one-tenth or less), the spectral quality is practically unchanged, owing to the relatively non-selective character of the transmission through water vapor. Similarly, the ultraviolet reflected from snow is extraordinarily high, owing to the fact that the ice crystals, within which the reflection occurs, are highly transparent to ultraviolet radiation.

The absorption of ultraviolet is caused by atmospheric pollution near the earth's surface, and by ozone in the stratosphere. An increase of 40 to 50 per cent. in intensity in the band of wave-lengths between 2,900 and 3,130A, is observed in rising 2 km (7,000 ft.) above sea level. A much greater

* Communicated by the Director.

increase in intensity may be expected at elevations of 15 to 25 km (10 to 15 miles). However, such heights are not practicable for large-scale biological tests.

The measurements at the Flagstaff station show a greater atmospheric transparency (less ozone) in the afternoon than in the forenoon; and a greater transparency in the autumn than in the spring. This is in agreement with the work of Dobson and others, using other methods of observation.

For the same solar altitude (that is for the same air mass traversed by the rays) the ultraviolet solar intensities in the tropics (at San Juan) were somewhat higher than at a mid-latitude, sea level station (Washington) that is free from local air pollution. This is in agreement with other observations showing that, in the tropics, for the same solar altitude the amount of atmospheric ozone is less, and consequently the ultraviolet intensities should be somewhat higher than in higher latitudes.

However, this small difference in intensity, for the same solar altitude, does not appear to be sufficient to produce marked differences in biological effects. If differences in biological effects that are ascribable exclusively to a difference in ultraviolet intensities are observable, they probably owe their origin to the fact that, for an interval of about 4 months (April 20 to August 20) at the noon hour, in the tropics, the sun shines through an air mass of $m = 1.00$ to 1.01, as compared with an air mass of $m = 1.04$ to 1.05 in mid-latitude (Washington). Consequently, during this period, the shortest, biologically most effective, wave-lengths (at 2,900A to 3,000A) are very greatly increased in intensity. The average intensity of the whole spectral band (at 2,900A to 3,130A, recognized as having a specific biologic action, at least in curing rickets) during the time when the sun shines through an air mass of $m = 1.00$ to 1.01, is about 20 per cent. higher in the tropics than is ever attained in mid-latitude.

Similarly, during the five winter months, at mid-latitude stations, the shortest, biologically most effective ultraviolet wave-lengths are almost completely absorbed, and the intensity of the less-effective wave-lengths is less than one-sixth the value that obtains in the tropics.

In addition to the greater intensity of the ultraviolet,

there usually is also a greater number of hours of sunshine in the tropics during the winter months. Other factors to be considered are differences in air movement, temperature, humidity, and the amount of clothing worn, all of which factors have an effect in reducing the incidence of rickets, which is practically unknown in the tropics.

HYDROTHERMAL SYNTHESIS OF KAOLINITE, DICKITE, BEIDELLITE, AND NONTRONITE.

RP819 in the *Journal of Research* for August describes the synthesis of some of the clay minerals, undertaken at the Bureau to throw some light on the stability relations of these minerals and on their origin in nature. Coprecipitated Al_2O_3-SiO_2 gels and mixtures of different forms of Al_2O_3 and SiO_2 were heated with water in a steel bomb at temperatures from 310° to 390° C., which produced pressures from 97 to 260 atmospheres. Kaolinite, dickite, and beidellite were successfully synthesized under different conditions of temperature and corresponding [illegible] ontronite, the analogue of beidellite containing ferric oxide instead of aluminum oxide, was also synthesized. The products were identified by X-ray patterns. The data obtained substantiate the conclusion of geologists that kaolinite, the essential constituent of most clays, is the result of low temperature weathering action on feldspar and similar minerals, while dickite and nacrite are formed by the action of water under pressure at higher temperatures.

SUBSTITUTION OF AMERICAN KAOLINS FOR ENGLISH CHINA CLAYS.

A paper on properties of American kaolins and their substitution for English china clays was published in the *Journal of the American Ceramic Society* for June, 1935. The properties in which the English and most of the American clays studied were different, were found to be refractoriness, color, strength after heat treatment at less than cone 7, linear thermal expansion, and shrinkage and porosity after heat treatment at all temperatures. These differences were traced primarily to fundamental differences in the amount of

fine-grained material present. The fact was brought out that the American kaolins contained less impurities than the English china clays. In order to obtain mixtures with properties similar to those of the English clays it was necessary to add fluxes such as feldspar and magnesium carbonate to the American clays. The paper contains data on chemical compositions, base exchange capacities, colloidal contents, transverse strengths, shrinkages, and porosities and thermal expansions of clays tested.

GASES EVOLVED FROM METALS ON HEATING.

Determination of the small amounts of the gaseous elements, oxygen, nitrogen and hydrogen which exist in a variety of forms and combinations in steel and many metals, has received a great deal of attention at the Bureau for several years past. This pioneer work has been supplemented by extended studies in numerous other laboratories.

For iron and steel samples the Bureau uses the vacuum-fusion method for determining oxygen, nitrogen, and hydrogen, although this method necessitates the use of rather elaborate equipment in the operation of which very considerable skill is required. Hitherto, these analyses have been time-consuming to the extent that a complete day's work was required for each sample. However, recent improvements in the apparatus and technique have more than doubled the speed with which determinations can be made. Determinations on as many as three samples can now be made in one day, apparently without any sacrifice of precision or reliability.

SERVICE LIFE OF STEEL FORGING.

A study of the properties of a metal after practical service use is usually very instructive particularly if the service conditions are unusual or severe. An examination was completed a short time ago in the Bureau's metallurgical division of a hollow cylindrical steel forging used as a reaction chamber for the high-pressure synthesis of ammonia. After approximately 8 years' use the cylinder was scrapped as a precautionary measure, and the examination was made in

order to determine to what extent the steel had deteriorated in this service, namely, contact with hydrogen and nitrogen under a pressure of several hundred atmospheres and at a temperature of approximately 150° C.

The tensile properties of the steel (2.54 per cent. chromium, 0.24 per cent. vanadium) close to the inner wall of the chamber did not differ from those of the steel in the middle of the section (2⅛ inch), and were identical with the results reported for the forging when it was made. The only suggestion of deterioration was a decarburized layer, 0.01 to 0.03 inch thick, on the inner wall of the chamber which, however, was too shallow to have any significant weakening effect on the strength of the cylinder. Other than this, there was no evidence of deterioration in the steel from the service to which it had been subjected.

DO METALS "CRYSTALLIZE" UNDER VIBRATION?

In published accounts of a recent endurance flight of an airplane, widespread publicity was given to the belief that metals may fail as a result of crystallization caused by vibration in service. This erroneous belief probably originated in an incorrect conclusion drawn from the typical appearance of the fractured surfaces of metals that failed after having been subjected to repeated cycles of service stresses.

It has been known for a long time that all metals in the solid state are aggregates of crystalline grains, generally of microscopic size. It is also known that the original crystalline structure cannot be altered by purely mechanical forces which do not permanently alter the outward form of the metal piece.

When a metal breaks from a single application of a force, the fracture takes place along natural cleavage planes through the crystal grains and the fracture exhibits a characteristic crystalline appearance. In ductile metals, fracture does not take place until considerable deformation has occurred.

However, when metals are subjected to repeated applications of force, fracture can occur without deformation, even in the most ductile metals, if the range or amplitude of the force exceeds a limiting value. For steels this value is gener-

ally about 50 per cent. of its strength under steady loads, but may be as low as 20 per cent. or as high as 60 per cent. This value is known as the endurance or "fatigue" limit. The fracture originates at a point where the stress is the maximum, or in some localized weakness. The crack itself, once started, is a localized weakness and grows with repeated stress application, generally perpendicularly to the direction of the applied forces.

As the advancing crack cuts off more and more of the sound metal, the load is carried by a progressively decreasing area, and finally sudden and complete rupture of the member occurs. The combination of the sudden break with the formation of a fracture which one is accustomed to find in very brittle materials is naturally disconcerting.

To one not familiar with the inherently crystalline structure of metals and the nature of the process of fracturing, it is perhaps only natural to conclude, from the observation of such a fracture that a portion of the metal had "crystallized" and therefore become brittle, and failed unexpectedly. Such a conclusion is nevertheless contrary to the known facts. A short "brittle" fracture in a metal is just as normal and characteristic as the more familiar "ductile" type.

LIGHT-WEIGHT CONSTRUCTION.

The Edgar Marburg Lecture for 1935 was delivered by Dr. L. B. Tuckerman of the Bureau's staff at the meeting of the American Society for Testing Materials in Detroit on June 26. While Dr. Tuckerman pointed out that all fields of science and technology have contributed to the development of the modern airplane, his paper was limited to the relations between the mechanical properties of material and the design of struts, beams, girders, stressed skin, etc., and the craft as a whole, to produce light-weight aircraft.

The major structural problem in aircraft is light-weight construction, and its significance was emphasized by a comparison of power-driven vehicles—locomotive, steamship, automobile, airplane, and airship—on the basis of their structural density, their structural fineness ratio, and the loads to which they are subjected. It was pointed out that

aircraft demand structures not merely lighter but of an entirely different order of lightness than had been necessary before. Success in meeting this demand has come from a combination of empirical design with theoretical investigations, and materials and structural tests of a volume unprecedented in the history of any comparable structural field.

Theoretical and experimental investigations all show that to secure light-weight construction the material must be spread out as far as possible from the axis of the structure or its structural elements. Typical light-weight construction is therefore thin-walled construction, i.e., thin webs, thin flanges, thin-walled tubes, thin sheet surfaces, etc. The limit of the spreading is set by local instabilities: wrinkling, twisting, crumpling or other types of collapse, of the thin material. The problem is to secure the best possible balance between plastic yielding, depending upon the strength-density ratio of the material, and major or local instabilities dependent upon its modulus-density ratio, and finally the transitions between them dependent upon an accurate knowledge of its stress-strain curve. These conclusions were illustrated by examples of simple structural members used in aircraft.

In the light of these conclusions the significant properties, density, strength-density ratio, and modulus-density ratio of selected materials were compared. The comparison showed that from these purely structural considerations there is little choice between the three types of construction now in use, wood, light aluminum alloys, and high strength alloy steels. The choice between them must be based on other considerations, ease of fabrication, resistance to deterioration by weathering, etc., and finally upon knowledge of the designs which will ultilize best the possibilities of the material.

Improvement in the quality of structural metals, which increases the ease of fabrication, and improvements in the technique of fabrication and joining of metal by such processes as riveting, crimping, soldering, brazing, and welding will make possible improved designs which are now impossible to fabricate.

With the best designs so far produced it is possible to utilize fully the strength of materials already available only in relatively small parts of the structure. The modulus-density

ratio is still the limiting property of the material and this ratio is practically unaltered by any treatment which can be given a material. Consequently no radical improvement in light-weight construction is at present to be expected from still further increasing the strength of the materials.

However, as our fund of knowledge increases, designs will be worked out that will make better use of materials now available, so as to utilize their strength more fully. It is along this line that great improvements are to be expected. Systematic tests on typical structural elements, covering ranges of materials, over-all dimensions, wall thicknesses, and types of loading should be made. Tests such as these promise material improvements in light-weight construction. While tests of this kind are being carried out in numerous laboratories, many more are needed if progress in light-weight construction is to be maintained.

In conclusion, Doctor Tuckerman pointed out that the principles, materials, and technique of light-weight construction, developed chiefly in connection with aircraft, are being increasingly used in other fields of construction, notably in the building of light-weight railroad trains.

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BOOK REVIEWS.

OSTERREICHISCHES FORSCHUNGSINSTITUT FÜR GESCHICHTE DER TECHNIK IN WIEN, BLÄTTER FÜR GESCHICHTE DER TECHNIK, Zweites Heft. Auer von Welsbach, von Ing. Dr. Franz Sedlacek, 85 pages, illustrations, 18 × 25 cms. Wien, Julius Springer, 1934.

Fifty years ago there gleamed in the Wiener Universität an incandescent light from gas and therewith began a new epoch for the entire gas lighting industry. It was one of the greatest discoveries of the time and it was due to the work of the immortal Carl Auer von Welsbach. In thankful memory of this great man the Kuratorium des Technischen Museums jointly with the Lichttechnische Gesellschaft in Wien make this presentation under the guidance of the Osterreichisches Forschungsinstitut für Geschichte der Technik. The booklet ably paints the picture of the life history of Welsbach in an informative, interesting and inspiring manner, and includes a narrative of his technical developments. It reveals a brief, thorough description of the life of his father, Alois Ritter Auer von Welsbach, an outstanding man in Vienna, particularly through his activities in the "Österreichische Staatsdruckerei" and the printing of natural illustrations. From this it can be drawn that Carl may have inherited some of the traits of his father which when developed through education produced the necessary elements

for technical research. However, Carl's education was obtained mainly through the responsibilities of his mother, for the elder Welsbach died when Carl was but eleven years of age.

The three great contributions to the world given by Carl Auer von Welsbach are the incandescent gas lighting, the osmium lamp, and the metal alloy used for sparking or igniting. Each was the result of genuine research and each was introduced during a period when it was most needed. They gave a tremendous impetus to the knowledge of the value of scientific research, which no doubt helped to forward it along other lines. Aside from this, we all know of their practical value.

Often known as the "Edison of Austria," Dr. Carl Auer von Welsbach was the recipient of the Cresson Gold Medal from The Franklin Institute, in the year 1901.

This booklet, in memory of the great inventor, contains a fund of information together with thirty illustrations. It is an admirable work written in clear terms readily intelligible to the layman.

R. H. OPPERMANN

ASSOCIATION THEORY OF SOLUTIONS AND INADEQUACY OF DISSOCIATION THEORY, by Jitendra Nath Rakshit, Rai Shaheb, F.I.C., F.C.S., Elliott Prizeman (Gold Medalist), Opium Chemist, Government of India. 297 pages, 18.6 × 14.4 cms. Calcutta, S. C. Auddy & Co., 1930.

This monograph sets forth the author's thesis for the association theory of solutions. So unusual in this day are the author's conceptions that we quote verbatim. On page 20 we find:

"Association theory of solution assumes that when a solute dissolves in a solvent a molecular combination takes place simultaneously as the formation of solution, in proportion same as their dilution, and when this proportion is disturbed or changed an immediate corresponding association of solvent and solute takes place uniformly. When this reaction takes place in solution along with the manifestation of disturbance of other properties, a change in volume is also accompanied, and this factor alone guides the alteration of specific gravity of solutions. The specific gravity curve of solutions is an expression of the force with which the molecules of solute and solvent are associated." This concept is amplified further on page 77: "All the molecules of the solvent and the solute being influenced by identical conditions it is unreasonable to presume that there should be a mixture of different kinds of combinations e.g. the ionised or the non-ionised. The process of association of the solvent and the solute is reversible at all conditions. The associated molecules of the solute and the solvent need not bear similarity to those of either component, in respect of chemical, electrical, optical, osmotic, etc., properties. Dilution, temperature and pressure influence the properties acquired by the associations of solvent and solute."

Rakshit examines solubility data, specific gravities, contractions in solutions, surface tensions, viscosities, osmotic pressures, thermal effects, optical properties and electrical effects successively, giving in each case a brief discussion of experimental methods and a sketchy development of its history. Considerable volumes of data, largely very old and of venerable historical interest, are introduced to show how empirical laws and theoretical relations adduced fail over the wide range

of conditions and systems examined. This is never particularly difficult but the writer might have made a stronger case had he utilized more modern data subject to less experimental uncertainty. There is not much evidence of comprehension of developments in physics and chemistry of the present generation, and words of appreciation for the efforts of such men as Ostwald, Arrhenius, Nernst, who did so much to erect a system of physical chemistry of enormous and tested practical utility, right or wrong, are lacking.

It would be unjust to consume so much space of time and paper were not some useful purpose to be served. The association theory has little chance of popularity as a working tool for it is essentially philosophical and negative in character. It provides neither quantitative relations nor means of prediction even of many qualitative phenomena. Thus it is not exposed to hazards of experimentation and confirmation of validity or lack thereof seems virtually impossible. It is an ocean big enough to swallow up the mightiest channels of quantitative thought. Nevertheless and despite the competence of physical chemists to shoot holes here and there in the rigid form presented (considerable difficulties are encountered especially with respect to electrolytic phenomena), the association theory (not altogether original with the author) sets forth a point of view worthy of the steel of advanced students and all teachers in the field. It is a radical concept, in conflict with half the physical chemistry now taught. So much of value to be gained here, and so few the workers have become!

LESLIE R. BACON.

THE STRUCTURE OF CRYSTALS, by Ralph W. G. Wyckoff, Supplement for 1930–1934 to the second edition. 240 pages, tables, illustrations, 16 × 23.5 cms. New York, Reinhold Publishing Corporation, 1935. Price $6.00.

As may be seen from the title, this book is a supplement for 1930–34 of Part II of the second edition of "The Structure of Crystals" and summarizes the new X-ray structure determination during this period. There are eleven chapters, all lettered A, corresponding in content to the similarly numbered chapters in the earlier work. This plan is also followed in the figure numbers. Chapter subjects include structures of the elements, of the type RX, RX_2, RX_3, etc., structures of hydrates and ammoniates and of miscellaneous inorganic compounds, of silicates, and of organic compounds.

An index of substances is appended as well as a bibliography of crystal structure data which is also a continuation of the previous book. Reference numbers throughout the body of the book apply to the bibliography.

This book is an American Chemical Society Monograph.

R. H. OPPERMANN.

PUBLICATIONS RECEIVED.

The Structure of Crystals, by Ralph W. G. Wyckoff, 240 pages, illustrations, tables, 16 × 23.5 cms. New York, Reinhold Publishing Corporation, 1935. Price $6.00.

Die Umwandlungen der Chemischen Elemente, von Arthur Haas, 118 pages, illustrations, tables, 15 × 23 cms. Berlin und Leipzig, Walter de Gruyter & Co., 1935.

Untersuchungen an Treibscheiben mit besonderer Reibkraft, von Dipl.-Ing. H. Herbst, unter Mitarbeit Dipl.-Ing. W. Berke und Dipl.-Ing. H. Schüssler, 78 pages, diagrams, 16.5 × 24 cms. Gelsenkirchen, Carl Bertenburg, 1935.

Blätter für Geschichte der Technik, Zweites Heft, Schriftleitung: Dr. Ing. L. Erhard. Auer von Welsbach, von Ing. Dr. Franz Sedlacek, 85 pages, illustrations, 17.5 × 25 cms. Wien, Julius Springer, 1934.

Chemical Analysis of Aluminum, Methods Standardized and Developed by the Chemists of Aluminum Company of America, under the direction of H. V. Churchill and R. W. Bridges. 81 pages, 13 × 21 cms. New Kensington, Aluminum Research Laboratories, 1935. Price fifty cents.

Impregnated Paper Insulation, the Inherent Electrical Properties, by J. B. Whitehead, Ph.D. 221 pages, diagrams, tables, 15.5 × 23.5 cms. New York, John Wiley & Sons, Inc. London, Chapman & Hall, Ltd., 1935. Price $4.00.

Premier Livre du Tétraèdre a l'Usage des Eleves de Premier, de Mathematiques des Candidats aux Grandes Ecoles et a l'Agregation, par P. Couderc et A. Balliccioni, preface de M. H. Villat. 199 pages, diagrams, 16.5 × 25 cms. Paris, Gauthier-Villars, 1935.

U. S. Coast and Geodetic Survey, Special Publication No. 189. First-Order Triangulation in Texas (1927 datum), by Hugh C. Mitchell. 431 pages, tables, maps, 15 × 23 cms. Washington, Government Printing Office, 1935. Price fifty cents.

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Carte géologique du massif du Mont-Blanc (Partie Française) à L'échelle du 1 : 20,000, par M. M. Paul Courbin et Nicolaus Oulianoff. Mont Dolent, avec notice explicative. Map 48 × 66 cms., descriptive pamphlet 13.5 × 21.5 cms. Paris, Librarie G. Jacquart, 1934. Price 20 francs.

CURRENT TOPICS.

Pneumatic Method of Installing Insulation.—What is believed to be the first time this method was used for locating insulation in hollow mullions and spandrels of a new structure is described in "Heating, Piping and Air Conditioning," Vol. 7, No. 7. In the St. Paul post office and custom house the mullions and spandrels were blown full of rock wool insulation to insulate the radiator risers and take-offs within them and to make the entire construction about the windows and over the spandrel areas non-conductive.

The pneumatic conveyor used for installing the insulation is standard equipment and consists of a gasoline engine power plant with built-in clutch, speed reducer, feeding device and blower. The feeder is surmounted by a hopper into which the rock wool is charged, thence to be blown through a rubber hose to the point of application. Operating pressure is about 3 lb. per sq. in. at the blower. About 48 tons of rock wool were used and about 57 days were required to complete the installation.

Over some areas, the insulation thickness is but 2 in.; over others it is 6 in. Considering the long period of time which the insulation will remain in service in this building it is evident that the low charges for depreciation will result in a low cost per year for the insulation, which in turn results in a larger net saving through reduced fuel requirements.

R. H. O.

The Photox.—This little generator is a new light-sensitive device, reported by EARL D. WILSON in the *Electric Journal* for July 1935 and has the unusual property of acting like a tiny primary battery when light strikes it. The Photox is a copper oxide photovoltaic cell having a sensitive element that consists simply of a copper disc 2.25 inches in diameter and 0.045 inch thick, coated with a thin film of red oxide. Upon the oxide is deposited a transparent film of metal to which electrical contact is made by means of a circumferential ring. The surface is protected from corrosive agents by a layer of varnish especially compounded to withstand temperature variations from $+50$ to $-50°$ C. The amount of current that such a cell will deliver externally is in general a function of the inherent photo-electric sensitivity, of the intensity of illumination, of the external series resistance, of the internal shunt resistance and of the

internal series resistance, the latter being located principally in the sensitive material.

This small device has already become the basis of several useful laboratory and commercial instruments. In connection with its use in camera exposure meters and foot-candle meters it is stated that there is no other photo-electric device known which has a natural unfiltered spectral response so close to that of the eye as the Photox. The Photox is most useful where appreciable response is desired at low intensities. For example, with galvanometers and portable meters up to say one microwatt rating, the Photox will give full scale deflection on 10 foot-candles or less, and the deflections will be quite linear with respect to intensity. The cell adapts itself to all sorts of differential circuits and a plurality of cells may be arranged in any sort of rectangular array to match the impedance of a given device

R. H. O.

Arma virumque cano, Trojae qui primus ab. . . .—What caption could be more fitting to a description of this year's commencement exercises at Rensselaer Polytechnic Institute? Just a century ago the first degree in engineering and in science granted in any English-speaking country was conferred at Troy, N. Y. In recognition of the anniversary, the honorary degree of doctor of engineering was bestowed upon Edward Wright Arms, who received the degree of civil engineer in 1869. Since he was born in 1845, his life has spanned all but ten years of the century of achievement at Rensselaer which is now being celebrated.

As a lad, before the Civil War, Mr. Arms had watched W. and L. E. Gurley adjusting the surveying instruments which they made famous throughout America. Before he even entered the Institute he had mastered the principles of construction and application of these instruments and, from a spyglass and brass protractors, had made for himself a transit. Since Troy, in 1860, was the recognized center for the manufacture of scientific instruments in the United States, he assisted many leading scientists in the development of the apparatus for which they are known. For Rudolf Hering he designed and constructed a device to test magnetically the wire employed in testing the materials used in the cables for the Brooklyn Bridge. Extending the Wollaston process, he produced for Samuel Pierpont Langley, the astronomer, a platinum wire, drawn to one fifty-thousandths of an inch, that made possible the bolometer designed by him for measuring the temperature of the stars. He also supplied the wire for the early coherers in the wireless telegraph.

Probably his most notable contribution was the production of

the first full automatic dividing engine in America. The success of Rowland's work on diffraction gratings, which was to some extent a refinement of the work which Mr. Arms had already completed, was due in no small measure to the latter's genius and generosity. His automatic screw machine, the first of its kind, marked the beginning of mass production. It was supplemented by other mechanisms, also automatic, for cutting racks and pinions. A lathe for thread-cutting and devices for figuring and finishing engines are included among his inventions.

Mr. Arms is better known, however, by the transits, including the first mountain transit, the levels, the alidades, and the meters which he designed and built. Always an explorer, he exhibited at the Exposition in Philadelphia, in 1876, an aluminum transit which was the first piece of fabricated aluminum in America. The fact that, across the aisle, Alexander Graham Bell, then a young man in his twenties, gave at the same time the first public exhibition of the telephone throws into sharp relief the length and significance of Mr. Arm's career.

C.

Modern Canal Planned for New Jersey.—VAN DYNE PELL. (*Excavating Engr.*, Vol. 24, No. 7). In 1930 Congress authorized an investigation by Army Engineers for the purpose of finding and recommending the most suitable route for a waterway across the state of New Jersey. Actual investigation continued for more than two years and included test borings and field surveys, as well as such studies as salinity, pollution, tidal conditions, vessel traffic and bridge, lock and dam design. The route strikes southwesterly across the narrowest part of the state for a distance of 31.5 miles—from the lowlands of the Raritan River near Sayreville to the Delaware River at Bordentown, four miles below Trenton. Completed plans, according to the Official Canal Report, provide for a canal at an elevation of ten feet above mean low water, a minimum depth of 25 ft., a bottom width of 250 ft., and side slopes of 2½ horizontal to 1 vertical. To maintain the canal level, suitable dams with adequate flood gates are proposed. Parallel locks for the passage of navigation are proposed at each dam. A low level lock canal was decided on because it is necessary to keep out intrusion of salt water from the Delaware River, since it is the source of municipal and industrial water supply for Philadelphia, other municipalities and for a large industrial region. The main function of the project is to provide a short, adequate water route between New York and Phila. to connect with existing waterways, thereby forming a protected inland route for coastwise shipping, ocean

tramp steamers, barges and other light craft between the principal North Atlantic ports from Norfolk to Boston. As compared to the present line of water travel via the Atlantic Ocean, around Cape May and up Delaware Bay, such a water route would reduce the sailing distance from the Battery in New York Harbor to the wharves at Philadelphia from 274 to 87 miles.

R. H. O.

A Continuous Gas Generating Process.—THEODORE NAGLE in the *American Gas Journal*, Vol. 143, No. 1, describes what is known as the flash system of carburetting, a system of continuous generation of carburetted blue-gas which eliminates the usual carburettor and superheater chambers with their periodic checker brick renewals, does away with solid fuel storage and handling as well as ash disposal and also eliminates the boiler plant for steam generation. A single shell gas machine is employed using oxygen and heavy oil. For the production of 1000 cu. ft. of 540 B.T.U. gas, the necessary ingredients are 5 gallons of oil (Bunker C or similar heavy oil) and for the necessary oxygen 4 K.W.H. Compressed air, from which the nitrogen is automatically separated through counter flow heat exchange liquefying and rectifying the air, provides a continuous electric power load for operating motor driven air compressors to produce a continuous supply of oxygen.

R. H. O.

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